AMERICAN SOCIETY
FOR
TESTING MATERIALS

ORGANIZED IN 1898
INCORPORATED IN 1902

PROCEEDINGS
OF THE
THIRTY-FIFTH ANNUAL MEETING

Held at Atlantic City, N. J.
June 20-24, 1932

VOLUME 32
PART II. TECHNICAL PAPERS

PUBLISHED BY
AMERICAN SOCIETY FOR TESTING MATERIALS
1315 Spruce Street, Philadelphia, Pa.

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American Society for Testing Materials

Printed in Philadelphia, U. S. A.
December, 1932

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American Society for Testing Materials

PROCEEDINGS, PART II

The Society is not responsible, as a body, for the statements and opinions advanced in this publication.

SUMMARY OF PROCEEDINGS OF THE CLEVELAND REGIONAL MEETING—SYMPOSIUM ON RUBBER

The third regional meeting of the Society was held in Cleveland at the Hotel Cleveland on Wednesday, March 9, 1932, in conjunction with the Spring Group Meeting of A.S.T.M. Committees. Arrangements for the regional meeting were under the auspices of the Cleveland District Committee. The meeting comprised a technical program, a Symposium on Rubber, to which both morning and afternoon sessions were devoted, followed by a dinner at which a paper on lighter-than-air ships, by Dr. Karl Arnstein, Vice-President, Goodyear Zeppelin Corp., was read by Mr. Hugh Allen. The paper was illustrated by motion pictures. President Clements gave a brief talk at the dinner pointing out the close relationship of the automotive and rubber industries and the importance of testing and research in the fields of the American industry. There were approximately 150 in attendance at the meeting.

The Symposium on Rubber was sponsored by the Society's Committee D-11 on Rubber Products and consisted of twelve papers as follows:

Morning Session

"The Extent and Diversity of the Rubber Industry," by Arthur W. Carpenter, Manager of Testing Laboratories, The B. F. Goodrich Co.

"Crude and Reclaimed Rubber," by R. H. Gerke, Development Dept., U. S. Rubber Co.

"Vulcanization," by N. A. Shepard, Director of Chemical Research, Firestone Tire and Rubber Co.

"Compounding: A Discussion of the Fillers, Reinforcing Agents and Softeners Used in the Compounding of Rubber," by R. H. Seeds, Development Dept., The Goodyear Tire and Rubber Co.

"Structures of Rubber in Combination with Textiles and Other Materials," by C. H. Zieme, Technical Superintendent, The Republic Rubber Co.

Afternoon Session

"The Flexing of Rubber Products," by E. G. Kimmich, Development Dept., The Goodyear Tire and Rubber Co.

"Shock and Vibration Properties of Rubber in the Automobile," by W. J. McCortney, Engineering Division, Chrysler Corp.

"Some Factors in the Deterioration of Rubber when Exposed to Frictional Contacts with Other Materials," by V. A. Cosler, Technical Superintendent, Hewitt-Gutta Percha Rubber Corp.

"The Chemical Resistance of Rubber as an Engineering Material," by H. E. Fritz, Manager, and J. R. Hoover, Assistant Manager, Chemical Sales Division, The B. F. Goodrich Co.

"Resistance of Rubber to Water and Gases," by R. H. Gerke, Development Dept., U. S. Rubber Co.

"Electrical Characteristics of Rubber Insulation," by E. W. Davis and G. J. Crowdes, Assistant Electrical Engineers, Simplex Wire and Cable Co.

"Rubber as an Adhesive," by J. J. Allen, Chief Compounder, and J. E. Beyer, Compounder, Mechanical Rubber Goods Division, Firestone Tire and Rubber Co.

The chairman of the morning session was H. E. Simmons, Professor of Chemistry at the University of Akron; and of the afternoon session, F. O. Clements, President, A.S.T.M.; Technical Director, General Motors Research Laboratories. The papers elicited a considerable amount of discussion which contributed greatly to the information contained in the papers. The papers, complete with discussion, have been published by the Society as a separate volume entitled, "Symposium on Rubber."

FUNDAMENTALS IN THE PROBLEM OF RESISTANCE TO DETERIORATION

EDGAR MARBURG LECTURE[1]

BY HUGH S. TAYLOR[2]

The problem of control in processes of deterioration is the problem of control of the speed of chemical reactions. The fundamental reactions in deterioration are oxidation processes involving oxygen, steam or other less universal oxidizing agents as well as reactions of polymerization, decomposition and depolymerization. Heat and light, ionization, pressure, and the presence of accelerating agents are the important factors which influence the speed of such processes and are thus of major importance in a discussion of the fundamentals of the problem. Control of deterioration is the inverse of the historical occupation of the chemist. Since alchemical times his prime concern has been the promotion of chemical reactions. A belated attention to the problem of preserving his synthetic achievements is not, however, without its own peculiar scientific interest and practical significance.

THE CONCEPT OF SPEED

Every chemist is familiar with the difference in reaction speeds of even essentially similar chemical processes. Thus in the combination of hydrogen and oxygen to form water, $2H_2 + O_2 = 2H_2O$, high temperature, ultra-violet light, reaction surfaces or the electric discharge are necessary if reaction is to be achieved. And yet, in an entirely analogous molecular process, $2NO + O_2 = 2NO_2$, the reaction proceeds so rapidly at ordinary temperatures that the brown fumes of the product are visible immediately after mixing. Such comparisons indicate that the velocity with which a chemical process occurs is dependent on some factor additional to that of concentration. The concentration determines the frequency of collisions between the reactants. But chemical reaction does not normally occur at every collision. Reactions which behave thus are liable to be explosive in nature. In all ordinary chemical reactions there is a collision efficiency factor which is of controlling importance in most cases since, in the majority of actual chemical operations, the variations in the concentration factor are not large. An example may serve to illustrate these points. The combination of two hydrogen iodide molecules to form hydrogen and iodine $2HI = H_2 + I_2$ occurs measurably fast at temperatures in the neighborhood of 300° C. From kinetic theory it is possible to calculate the number of collisions that occur between two molecules under any given conditions of concentration and temperature by means of the equation:

---

[1] Read on June 22, 1932, before the Annual Meeting of the American Society for Testing Materials, Atlantic City, N. J.

[2] David B. Jones Professor of Chemistry, Princeton University, Princeton, N. J.

$$z = 2\sqrt{2\pi}\,\frac{n_1 n_2}{v^2}\left(\frac{d_1 + d_2}{2}\right)^2\sqrt{\frac{m_1 + m_2}{m_1 m_2}\cdot kT}\ldots\ldots\ldots\ldots(1)$$

where n_1 and n_2 are the numbers of any two types of colliding molecules in volume v, with collision diameters, d_1 and d_2, and molecular masses, m_1 and m_2, k being the Boltzman constant. For like molecules colliding this reduces to:[1]

$$z = \frac{n^2}{v^2}d^2\sqrt{\frac{4\pi\, kT}{m}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

A comparison of the collision numbers so calculated and the actual number of reacting molecules indicates that at a temperature of 600° Abs. (327° C.) the collision efficiency factor is only 10^{-16}, a very small number. This efficiency factor changes rapidly with temperature but at a temperature of 781° Abs., where the velocity of reaction is almost too rapid to measure conveniently, the ratio of effective to total collisions is still only 10^{-12}. Indeed we may state as a general rule that in a temperature and pressure range where molecular reactions are easily measurable the order of magnitude of effective collisions is one in a million million total collisions. The rate of a reaction, k, is the product of the total number of collisions and the efficiency factor. Since this latter varies with temperature it has been found possible to express it as a function of the absolute temperature of the form $e^{\frac{-E}{RT}}$ so that the velocity equation is:

$$k = z \cdot e^{\frac{-E}{RT}}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where z is the total number of collisions given by Eq. 1 or 2, and the efficiency factor is an exponential in terms of the absolute temperature, T, the gas constant, R, and an energy quantity, E, which we may term the activation energy, a characteristic quantity for each reaction. The smaller the value of E, obviously, the faster will a reaction occur at a given temperature. Or, returning to our two reactions, $2H_2 + O_2 = 2H_2O$ and $2NO + O_2 = 2NO_2$, we can say that the activation energy of the former is very much larger than that of the latter.

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[1] See K. F. Herzfeld and H. M. Smallwood, "Treatise on Physical Chemistry," Chapter II, p. 124, 2nd Edition, D. VanNostrand Co., New York City (1931).

Activation Energy:

Some twenty years ago an explanation of this inefficiency of collisions and of the accelerating effect of temperature was formulated. The conclusion was reached that only those collisions whose joint energy exceeded a certain definite minimum of energy would result in chemical change. This energy, which we have called the activation energy, is attained the more frequently the higher the temperature, and, according to kinetic theory calculations, in just the relationship given above and required by the experimental observations on the effect of heat on speed of reaction. The activation energy, then, is the minimum energy which an atomic or molecular system in its initial state must achieve over and above the average energy of that state in order to pass to the final state of reaction product.

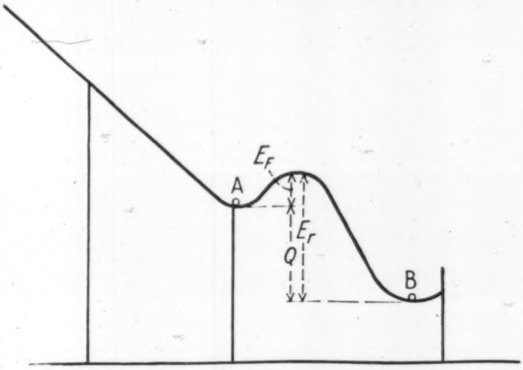

FIG. 1.—Roller Coaster Model to Illustrate Activation Energy.

The process may readily be illustrated with the aid of a miniature roller coaster and a pair of marbles (Fig. 1). With small energy increments due to collisions the system will remain in the energy valley, *A*, of the reactant molecules. The greater the violence of the collisions the more probable the attainment of energy sufficient for one to pass over into the energy valley, *B*, which represents the reaction products. The model also shows that the minimum energy necessary is less for those reactions which occur with evolution of energy. (Transitions on the roller coaster from higher level, *A*, to lower level, *B*.) It is greater for the reverse process which occurs with an absorption of heat by an amount equal to this energy difference, *Q*, between the initial and final states:

$$E_r - E_f = Q$$

where *r* represents reverse and *f* forward. The higher the activation energy required the more violent the collisions required, or what is the same thing, the higher the temperature necessary for a given speed of reaction.

Reactions Involving Atoms and Radicals:

Reactions between molecular species require in general marked activation energies; their collision efficiencies for reaction are, as already stated, low. During the past decade, experimental and theoretical research has shown that interactions between atoms or radicals and molecules possess a very much higher order of collision efficiencies. Many reactions between atomic species and molecules occur practically at every collision. Thus, Polanyi and his coworkers[1] studied a series of reactions between alkali vapors and the halogens and alkyl halides, as, for example:

$$Na + I_2 = NaI + I$$
$$Na + CH_3I = NaI + CH_3$$

Since these "elementary reactions" occurred at every collision a special technique involving studies at micropressures was necessary. The reactions were slowed down in tempo by reducing the concentration term in Eq. 3. Polanyi's first results indicated that, whenever the "elementary reaction" was exothermic, such reactions in general occurred on every collision. More recently it has been shown that this rule is not completely general. Thus, the interaction of sodium vapor and methyl fluoride, $CH_3F + Na = NaF + CH_3$, although markedly exothermic, is, nevertheless, slow and requires a marked activation energy (>20,000 cal.). Atomic reactions involving hydrogen molecules as, for example:

$$Cl + H_2 = HCl + H$$
$$O + H_2 = OH + H$$
$$OH + H_2 = H_2O + H$$

while exothermic in character do not occur at every collision, the three examples cited requiring activation energies of the order of 5 to 10 kg-cal. When such reactions are endothermic in nature as, for example, the interaction of bromine atoms and hydrogen molecules, $Br + H_2 = HBr + H - 17$ kg-cal., the activation energy of the reaction cannot be less than 17 kg-cal. and may be a few kilogram calories greater than this value.

---

[1] G. Schay, "Highly Dilute Flames," Fortschritte der Chemie, *Physik und physikalische Chemie*, Vol. 21, No. 1, p. 1 (1930); M. Polanyi and H. Beutler, S. von Bogdandy, G. Schay and H. Ootuka, "Highly Dilute Flames," *Zeitschrift für physikalische Chemie*, Vol. 1, Abteilung B, p. 3 (1928); H. von Hartel and M. Polanyi, "Atom Reactions Having Activation Energy," *Zeitschrift für physikalische Chemie*, Vol. 11, Abteilung B, p. 97 (1930); G. Schay, "Highly Dilute Flames of Alkali Metal Vapors with Hydrogen Halides," *Zeitschrift für physikalische Chemie*, Vol. 11, Abteilung B, p. 291 (1930).

The importance of such atom or radical reactions lies in the possibility of their being intermediate stages in the process of reactions between molecules. This was suggested by Nernst in his discussion of the hydrogen-chlorine photochemical reaction, according to which, with the light absorption producing two Cl atoms from an absorbing Cl_2 molecule, a sequence of rapid reactions, $Cl + H_2 = HCl + H$ and $H + Cl_2 = HCl + Cl$, was possible. This suggestion of an atomic chain became, as we shall see, fundamental in the discussion of reactions many of which are of importance in problems of deterioration. The practically simultaneous suggestion by Christiansen, Herzfeld and Polanyi of a similar atom chain mechanism for the thermal combination of hydrogen and bromine in which the sequence of reactions is:

$$\begin{aligned} Br_2 &= 2\,Br \quad \ldots\ldots\ldots\ldots (a)\\ Br + H_2 &= HBr + H \quad \ldots\ldots\ldots\ldots (b)\\ H + Br_2 &= HBr + Br \quad \ldots\ldots\ldots\ldots (c)\\ H + HBr &= H_2 + Br \quad \ldots\ldots\ldots\ldots (d) \end{aligned}$$

extended the idea of such rapid intermediate atomic reactions to thermal processes. Reaction *(b)* of this sequence is the endothermic reaction already discussed which, with bromine atoms produced by light absorption, determines the effect of temperature on the whole reaction. Reaction *(d)* accounts for the inhibitory action of hydrogen bromide on the reaction, a factor discovered by Bodenstein and Lind[1] in their much earlier experimental studies but unexplained by them and not understood prior to the formulation of the atomic chain mechanism. This mechanism provided the explanation for the differences between the kinetics of the two reactions:

$$\begin{aligned} H_2 + I_2 &= 2\,HI\\ H_2 + Br_2 &= 2\,HBr \end{aligned}$$

Whereas the former is a simple bimolecular collision reaction, the latter does not so occur because the activation energy of the bimolecular collision reaction is much higher than that of the alternative atomic chain mechanism cited above. The path from the initial to the final state which involves the lower activation energy is the preferred path, will occur more frequently.

It is pertinent here to call attention to newer methods of approach to this problem of velocity of chemical processes because they are beginning to yield methods for the *calculation* of velocities of reaction, at any rate in the simpler atomic and molecular processes.

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[1] M. Bodenstein and S. C. Lind, "Velocity of Formation of Hydrogen Bromide from Its Elements," *Zeitschrift für physikalische Chemie,* Vol. 57, p. 168 (1907).

The accepted concepts of atomic structure now make possible a determination of the mutual potential energies of atomic systems. For two atoms, we can, with Franck and Condon, set up from spectroscopic data a potential energy curve representing the mutual attraction and repulsion of two atoms, *A* and *B*, at varying distances apart. These attractions and repulsions will be modified by the proximity of a third atom, *C*, to an extent now calculable from quantum mechanical bases. By making such computations and the similar calculations for a molecule, *AC*, with approaching atom, *B*, it is possible to compute the potential energy of the system of atoms, *A*, *B* and *C*, at any distances of the three from each other. We can embody the results of such a study in a potential energy surface, the form of which can readily be seen from the accompanying contour map (Fig. 2). A glance will show what is the easiest pathway which the system $AB + C$ can take in order to reach the end system $AC + B$. The easiest path so far as energy content is concerned is along the valley route between the precipitous hill slopes on each side. An examination of the contour of this valley floor indicates first a gentle rise, the activation energy of the reaction $AB + C$, secondly a shallow trough corresponding to a possible compound *ABC* but so shallow that the energy of the system in motion is more than adequate to

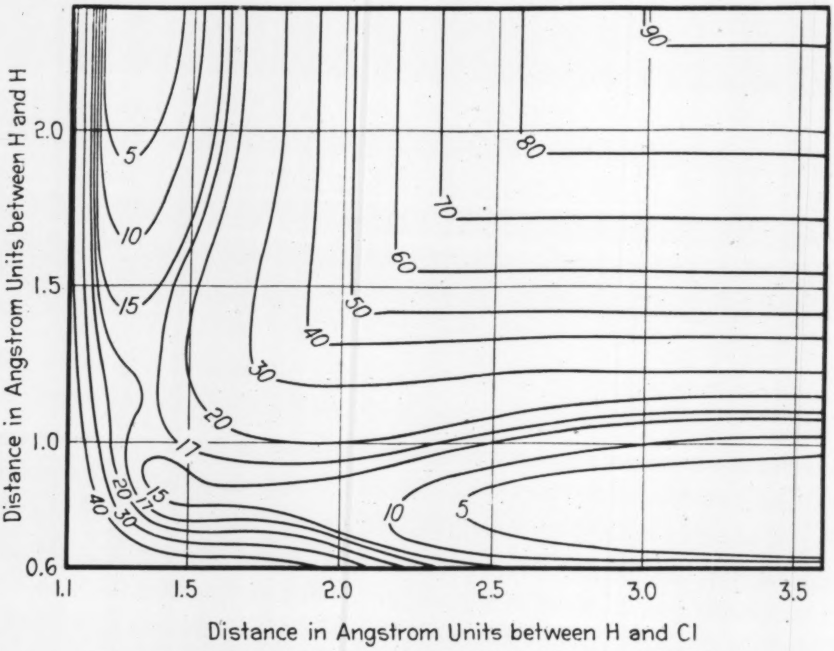

FIG. 2.—Potential Energy in kg-cal. of the System H-H-Cl.

carry it through the trough over a tiny saddle once more to the final end state $AC + B$. The progress of a marble along this valley floor faithfully imitates the behavior of such an atomic system. More recently Eyring and his associates[1] have extended this method to more complex reactions between molecules.

Such calculations abundantly verify the conclusions which we have just reached. Thus, in the hydrogen-bromine combination, the bimolecular collision process is found to have an activation energy greater than 43,000 cal. The atomic chain mechanism is known to be less than 30,000 cal. With iodine and hydrogen the reverse is true, calculations indicating that the atomic chain mechanism requires 18,000 cal. larger activation energy. Perhaps, however, the most striking result from the calculations is the very definite conclusion that hydrogen and fluorine molecules do not react at room temperatures and that even fluorine atoms would show little reactivity with hydrogen molecules at room temperatures. This conclusion is very emphatically contradicted by all the textbooks of inorganic chemistry, but the textbooks are wrong and have been so for the generations that have elapsed since the original Moissan-Dewar experiments. For, as has recently been shown by von Wartenburg and his associates,[2] neither atomic nor molecular fluorine, *when pure*, show any reactivity towards hydrogen at ordinary temperatures. The slowness of reaction between sodium vapor and methyl fluoride, which we have already discussed, is a parallel case of slow reaction velocity in fluorine compounds.

These general remarks on the incidence of atomic reactions in processes which, in their summation, involve reactions between molecules and may, by their occurrence, increase the speed of such processes, have been introduced into the present discussion because it will emerge that many of the reactions involved in processes of deterioration are such that chains of rapid reactions involving atoms or radicals may play an important rôle. Procedures designed to minimize the occurrence of such reactions, or their suppression if inevitable, are an essential part of the technique involved in the control of deterioration.

Relative Effects of Collision and Efficiency Factors:

A change in the velocity of chemical reaction at a given temperature can be secured, as Eq. 3 shows, either by a modification of the collision factor, z, or the activation energy, E. Of these two factors the latter is by far the more important in its influence on velocity. Examination of Eqs. 1 and 2 will reveal that the only possible variable in z at constant temperature is the concentration term, $\frac{n_1 n_2}{v^2}$. Since the concentration appears (for a bimolecular reaction) as the square, it follows that changing the pressure in a gas reaction (the worst case) to 0.001 or to 1000 atmospheres, only influences the velocity by a factor $10^{\pm 6}$. With liquid or solid systems the variation in $\frac{n_1 n_2}{v^2}$ would be considerably less. On the other hand, by reducing the activation energy, E, or by raising the temperature, T, Eq. 3 shows that an exponential change may be secured in the value of k, the velocity of reaction. Thus, for example, if a bimolecular reaction with an activation energy E of 40,000 cal. and occurring negligibly at room temperatures ($T = 300°$ Abs.) be converted into a sequence of reactions of which the maximum activation energy of the constituent steps was only 10,000 cal., a change in velocity equal to $e^{\frac{-(40,000-10,000)}{RT}} = e^{\frac{-30,000}{600}} = e^{-50} = 10^{-22}$ fold would result.

---

[1] H. Eyring, "The Energy of Activation of Bimolecular Reactions Involving Hydrogen and the Halogens, According to the Quantum Mechanics," *Journal*, Am. Chemical Soc., Vol. 53, p. 2537 (1931).

[2] H. von Wartenburg and J. Taylor, "Heat of Dissociation of Fluorine," *Göttinger Nachrichten*, Heft 1, p. 119 (1930).

Activation Energy Lowered by Catalysts:

The resolution of a reaction into a series of steps, each with an activation energy markedly inferior to that of the single stage process is, in reality, the objective pursued in a search for a catalyst for a reaction. Thus, if a reaction, $A + B = AB$ with an activation energy E_1 at a temperature T can be resolved with the aid of a catalyst C into two steps,

$$A + C = AC$$
$$AC + B = AB + C$$

with activation energies E_2 and E_3 markedly less than E_1, then, as the numerical example just cited shows, enormous changes in the rate of reaction can be secured.

Surfaces.—As is well known, surfaces are excellent agencies for securing such stepwise attainment of slow reactions. An index of the efficiency factor of a surface in the promotion of chemical reactions may be obtained by a consideration of a reaction recently studied by Pease at Princeton both as a homogeneous collision gas reaction (activation energy, E homogeneous = 43,000 cal.) and also as a surface reaction in contact with copper. The reaction is the simple one just discussed, $A + B = AB$, hydrogen and ethylene forming ethane. The collision reaction proceeds at 500° C. at about the same speed as the surface reaction at 0° C. From the activation energy of the high temperature process we are able to calculate from the data of Pease how fast the reaction would proceed by collision at the temperature of 0° C. at which it proceeds measurably rapidly on the copper surface. The result is illuminating. The presence of the copper produces an acceleration of the simple collision process of the order of 10 million, million, million fold. This example represents a small, rather than a high, surface efficiency. The azo-bacter, a bacterium which fixes the nitrogen of the air at room temperatures possibly operates by a surface process analogous to ammonia synthesis. If this be true one can compute that the acceleration produced by such bacteria over the normal rate of gaseous collision reaction must be of the order of 10^{72} or one million raised to the twelfth power.

These surfaces operate by splitting a reaction with high activation energy into a number of successive steps each of which has a characteristic activation energy markedly smaller than that of the simple process. The longer path is the more speedy because the increments of energy at each step are less. The analogy of the zigzag path up the mountain face instead of the direct assault conveys something of the idea involved.

Recently, Sherman and Eyring[1] have made a theoretical calculation, which accords with practical experience, that the tearing apart of the two atoms in a molecule of hydrogen, a process which ordinarily would require 100,000 cal. of energy per mole, and is normally achieved only on high temperature tungsten filaments or in the atomic hydrogen torch or by means of a high-tension discharge, is achieved at room temperatures and even at lower temperatures on suitably spaced carbon atom surfaces with less than one-tenth of the activation energy required for the homogeneous gaseous process. Thus achieved, the hydrogen atoms obtained are not free, but are attached to the carbon surface, with only, however, approximately one-half the energy with which they were bound to one another in the molecule. This follows from the observation that the heat of adsorption on the surface is very small. By reason of their weaker binding to the carbon atoms than to one another in the molecule, the greater potential reactivity of hydrogen atoms at such a surface arises.

Homogeneous Catalysts.—The ideas outlined already with respect to the influence of surfaces on the activation energy of chemical reactions are equally applicable to reactions in homogeneous media. The substitution, for a reaction with high activation energy, of a stepwise series of reactions leading to the same end point, the steps each having markedly lower activation energies, will produce a marked increase in reaction velocity. As an example of this kind we shall choose a reaction which for other reasons also is fundamental in the problem of deterioration; we refer to the oxidation of sodium sulfite. It has been definitely established by the work of Titoff[1] that, in solutions of the highest purity, the oxidation of sodium sulfite by dissolved oxygen is negligibly small. In the present terminology the reaction possesses a relatively high activation energy. Titoff, however, was able to show that the oxidation process was enormously accelerated by extremely minute amounts of various ions, the most notable example being the copper ion, which, even in a concentration as low as 10^{-13} molar, produced a perceptible acceleration of the oxidation of such solutions. The mechanism of the action of the copper ion has recently been set forth by Haber and his associates in a comprehensive series of investigations,[2] dealing with various aspects of the autoxidation problem. The action of the cupric ion is to interact with the sulfite ion to form the ion SO_3' of a weak acid, HSO_3, which, as it represents one half of the acid dithionic acid, may be termed monothionic acid. The equation for its production would read:

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[1] A. Sherman and H. Eyring, "Quantum Mechanics of Activated Adsorption," *Journal*, Am. Chemical Soc., Vol. 54, p. 2661 (1932).

$$\mathrm{Cu}^{\cdot\cdot} + \mathrm{SO}_3'' = \mathrm{Cu}^{\cdot} + \mathrm{SO}_3' \ldots\ldots\ldots\ldots (a)$$

The stable form of this univalent ion is its dimer the dithionate ion:

$$2\,\mathrm{SO}_3' = \mathrm{S}_2\mathrm{O}_6'' \ldots\ldots\ldots\ldots (b)$$

and dithionate is the major product of the interaction of cupric ions and sulfite ions in the absence of oxygen, as was early shown by Baubigny.[3] With dissolved oxygen present in the system, the formation of dithionate ion by dimerization, owing to the low concentration of SO_3' and the consequent low probability of encounter between two such ions, is subordinate to the interaction of the monothionic acid with oxygen to form HSO_5 and the reaction of the latter with SO_3'' to form 2 SO_4'', thus:

$$\mathrm{HSO}_3 + \mathrm{O}_2 = \mathrm{HSO}_5 \ldots\ldots\ldots\ldots (c)$$

$$\mathrm{HSO}_5 + \mathrm{SO}_3'' + \mathrm{H}_2\mathrm{O} = 2\,\mathrm{SO}_4'' + \mathrm{OH} + 2\,\mathrm{H} \ldots\ldots\ldots\ldots (d)$$

Reaction (*c*) will have a low activation energy because of the radical-like character of the HSO_3. The moloxide formed, HSO_5, is assumed to possess in common with other moloxides a tendency to rapid reaction.

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[1] A. Titoff, "Contributions to the Knowledge of Negative Catalysis in Homogeneous Systems," *Zeitschrift für physikalische Chemie*, Vol. 45, p. 641 (1903).

[2] F. Haber, "On Autoxidation," *Die Naturwissenschaften*, Vol. 22, p. 450 (1931); F. Haber and J. Franck, "On the Theory of Catalysis by Heavy Metal Ions in Aqueous Solutions and Especially on the Autoxidation of Sulphite Solutions," *Sitzungsberichte* der Preussischen Akademie der Wissenschaften, Vol. 1930, p. 250 (1930); H. Albu and H. D. von Schweinitz, "On the Formation of Dithionate by Oxidation of Aqueous Sulphite Solutions," *Berichte* der Deutschen Chemischen Gesellschaft, Vol. 65, p. 729 (1932).

[3] H. Baubigny, "On the Formation of Dithionic Acid," *Comptes Rendus* de l'Academie des Sciences (Paris), Vol. 154, p. 701 (1912); *Annales de Chimie et de Physique*, Vol. 20, 8th series, p. 5 (1910); *Annales de Chimie*, Vol. 1, 9th series, p. 201 (1914).

Haber supports the mechanism proposed by demonstrating that all reaction conditions which in presence of dissolved oxygen favor sulfate formation yield, in the absence of oxygen, dithionate. Oxidation agents such as hydrogen peroxide, potassium persulfate and potassium permanganate accelerate autoxidation and also yield dithionate in absence of oxygen. Dithionate is also formed at unattacked anodes on electrolysis of sulfite solutions and, similarly, oxygen consumption by sulfite solutions in the anode compartment during electrolysis is markedly greater than in the absence of electrolysis. Similarly, ultra-violet light absorbed by sulfite solutions increases enormously the oxygen absorption and also produces dithionate in absence of oxygen.

One feature of fundamental significance in the problem of sulfite oxidation, to be dealt with more in detail in subsequent sections, may be exhibited before the discussion of this reaction is closed. An examination of reaction (*d*) above indicates that the sulfate ion formation is accompanied by the simultaneous formation of the hydroxyl radical. It must be pointed out that the rapid interaction of this highly reactive radical with a sulfite ion according to the equation

$$SO_3'' + OH = SO_3' + OH' \ldots\ldots\ldots\ldots\ldots\ldots (e)$$

regenerates an ion of monothionic acid such as was produced with the aid of the cupric ion in reaction (*a*). Such an ion may obviously repeat the cycle (*c*), (*d*) and (*e*) either indefinitely or until one of the stages in the cycle is rendered impossible by alternative reactions. Reaction (*b*) of our scheme is one such alternative which would break the sequence. It is, however, evident that, by a sequence of reactions which are self-perpetuating, a whole cycle of processes may succeed an initial impulse provided by the cupric ion. We shall see, in the sequel, that such reactions, the so-called "chain reactions," are by no means infrequent in the problems of deterioration. Their existence multiplies the accelerating effect due to the presence of the reaction initiator—in this case the cupric ion. It should be emphasized, however, that the existence of a chain mechanism is not a necessary concomitant of a reaction sequence which occurs with lower activation energy and hence more rapidly than the uncatalyzed reaction. There are many reactions which do not involve chains, in which the presence of an active agent, whether a surface or homogeneously distributed throughout the reaction medium, brings about a succession of reactions with a given end point more rapidly than the same process can be achieved in the absence of such accelerants.

Prevention of Deterioration in Catalyzed Reactions:

The problem of the prevention of deterioration in such systems is the problem of ensuring the effective absence of such surfaces or homogeneous catalysts as may initiate the faster reaction sequence. We may term this type *the inhibition of deterioration by reduction of the concentration of a positive catalyst.* At one time it was very generally believed that this constituted the sole method by which reduction in the speed of chemical change and, more specifically, the prevention of deterioration could be secured. The subsequent sections will indicate that this is far from correct. Nevertheless, this category of preservation is an important one, as the discussion of examples will subsequently show. Many materials may be successfully protected against deterioration by removal of all materials which permit a reaction path of lower activation energy than the deterioration reaction itself possesses. In general this type of catalyzed deterioration is identified in all those cases in which progressive purification of the desired material leads to a progressively increasing permanence.

Inhibition of Reactions by Lowering the Concentration of a Reactant:

We may now consider briefly the category of inhibition phenomena in which reaction is suppressed by reduction in the concentration of a reacting species. As earlier noted, there are theoretical reasons why such methods involving as they do the z factor of Eq. 3 may not be so pronounced in their efficacy as methods just discussed involving the activation energy. It is obvious, however, that a process of deterioration involving oxidation by atmospheric oxygen may be diminished in its incidence by any arrangement which ensures that the concentration of atmospheric oxygen accessible to the material shall be reduced, if possible, to a minimum. The simple device of storing oxidizable analytical solutions in an atmosphere of an inert or reducing gas is one illustration of this procedure. The coating of an oxidizable film with a covering impervious to oxygen is another illustration.

An important group of reactions to which the method of reduction of concentration of a reacting species is applicable is that in which one of the reactants undergoing change is the ion or molecule of an electrolyte. If the ion be the more reactive, the undissociated electrolyte being either non-reactive or of a lower order of activity than the ion, inhibition will occur whenever any substance is added to the system which represses the dissociation of the electrolyte whose ion is reactive. Conversely, in any reaction in which the undissociated electrolyte is more reactive than its ions, inhibition will occur when, to the reaction system, substances are added which will increase the electrolytic dissociation. If, in a reaction of either type just mentioned, an inhibitor of this kind results from the reaction the system will show auto-inhibition or auto-retardation. But the converse is also true, and a product may result which accelerates the change, in which case addition of substances designed to suppress the concentration of a catalyst is necessary.

The hydrolyses of halogen substituted organic acids are examples to which the considerations just discussed apply. Hydrobromic acid inhibits the hydrolysis of bromosuccinic acid, evidently because the ion is more reactive than the undissociated molecule. The retardation is inversely proportional to the hydrobromic acid concentration.[1] The same action of hydrogen halides is observed in the hydrolysis of the several halogen acids of acetic, propionic and butyric acids.[2]

Light-sensitive Processes:

Many reaction systems relatively quite stable in the dark undergo chemical change when exposed to light. It is the absorbed light which is the source of the activation energy of the system. This does not mean that all light absorbed will produce chemical change. The stability of numerous colored materials is proof of this. Of the total light absorbed only certain regions of absorption may produce chemical change. The type of change may be dependent also on the nature of the light absorbed. Thus, one region may produce oxidation reactions, another decomposition or polymerization.

The simplest cases of photo-change are those in which there is a one-to-one relationship between the light energy absorbed and the chemical change produced. The light energy is measured in terms of quanta of monochromatic light, each equal to $h\nu$, where ν is the frequency or reciprocal wave length of the light and h is the quantum constant = 6.55×10^{27} erg seconds; the chemical energy is expressed as the number of molecules reacting. Each molecule receiving a quantum of light energy becomes activated and enters upon its characteristic chemical change. In all such cases, the only method available to prevent the process occurring is the physical method of suppression of the light energy absorption. This may be accomplished by external light filters. Glass filters are useful when it is merely a question of preventing the access of visible light. The use of suitably colored glasses, for example brown or yellow glass, is resorted to in case the blue or violet region of the spectrum is active. It may be that a substance can be added to the reaction system which absorbs in that region of the spectrum to which the reactant is sensitive. The foreign substance may dissipate the light it absorbs without transferring the energy to the reactant, thus acting as an "internal light filter." Examples of this type of screening effect were noted by Anderson and Taylor[1] in studies of the inhibition of hydrogen peroxide decomposition. It was shown, however, in many of the cases studied that the inhibitors acted more efficiently when in the peroxide solution than when in a screening solution of equivalent thickness and concentration. This is doubtless to be associated with the chain characteristics of peroxide decomposition subsequently to be discussed. Alyea and Jeu[2] have recently suggested that a screening effect may be found within the reacting molecule itself, as, for example, in the photochemical decomposition of acetaldehyde into carbon monoxide and methane. Two absorption bands are known: one, involving the CH_3 group has its maximum well below 2000 Å., the other has a maximum at 2800 Å., the absorption falling to negligible amounts below 2200 Å. In the region 2400 to 2200 Å., both types of absorption occur but only the $>CO$ absorption leads to decomposition. Since, at 2200 Å., most of the absorption is by the CH_3 groups, these radicals may be acting as internal light filters, robbing the $>CO$ group of the light which it might use to decompose the molecule. Alyea and Jeu suggest that such an intramolecular screening may be operative in the photo-polymerization of vinyl acetate studied by Taylor and Vernon[3] where low quantum yields were obtained at 2300 and 2536 Å., whereas, in the region 3000 to 4000 Å. high quantum yields, averaging 1000 molecules polymerized per absorbed quantum were obtained.

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[1] W. Müller, "On the Velocity of Decomposition of Brom-succinic Acid in Aqueous Solution," *Zeitschrift für physikalische Chemie*, Vol. 41, p. 483 (1902).

[2] G. Senter and A. W. Porter, "The Mechanism of Negative Catalysis," *Journal*, Chemical Soc., Vol. 99, p. 1049 (1911).

An important example of photo-deterioration, which belongs to the category under discussion, is the decomposition of nitrocellulose film by light. The best available evidence indicates that the quantum yield, the number of molecules decomposed per light quantum absorbed, is unity or less. Hence, screening or physical protection appears to be the only possible method at present for stabilizing such film against light action. Use has already been made of protective coatings of waxes containing light-absorbing materials. A variety of photoreactions occur, in part dependent on the wave length, which profoundly modify the film characteristics.[4] The film becomes acid, its brittleness increases, its tensile strength decreases, a yellow color develops. The change in the colloid is profound since the viscosity of a solution of irradiated film is lower than that of the solution from which the film was cast. Extended irradiation may yield material without marked influence on the viscosity of the solvent medium.

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[1] W. T. Anderson and H. S. Taylor, "The Inhibition of the Photochemical Decomposition of Hydrogen Peroxide Solutions, Parts I and II," *Journal*, Am. Chemical Soc., Vol. 45, pp. 650, 1210 (1923).

[2] K. K. Jeu, "Comparative Inhibitory Powers of Organic Substances in Chain Reactions," Thesis, Princeton (1932).

[3] H. S. Taylor and A. A. Vernon, "The Photo-polymerisation of Styrene and Vinyl Acetate," *Journal*, Am. Chemical Soc., Vol. 53, p. 2527 (1931).

[4] H. B. De Vore, A. H. Pfund and V. Cofman, "A Study of the Action of Light of Different Wave-Lengths on Nitrocellulose," *Journal of Physical Chemistry*, Vol. 33, p. 1836 (1929).

In the extreme ultra-violet light from 1900 to 2600 Å., the reactions occurring are decomposition reactions which materially reduce the film thickness. The absorption of such light by the film is very strong and hence the action of the light is confined to the surface of the film. Acidity develops in the film with light from 2300 to 6000 Å. with a strong maximum around 3130 Å. In this region the absorption is more moderate so that the acid-forming decomposition is distributed throughout the film. Brittleness is most markedly produced by light in the region around 2537 Å., very much more rapidly than by the longer wave lengths. The long wave length region from 2300 Å. upwards produces an increased solubility of and imbibition by the film.

One aspect of the use of "internal light filters" by incorporation of the absorbing material within the body of the material to be protected must here be emphasized. Use of an internal light filter is effective only if the energy absorbed by the added agent can be dissipated without transfer to the reactant. The phenomenon of "photosensitization," familiar to the photographer in the production of panchromatic and orthochromatic film, indicates that a material may be sensitized to light otherwise ineffective by incorporation of light absorbing materials in the reaction system. The added agent absorbs and transfers the energy to the reactant. This accounts for numerous observations; for example, in the case of nitrocellulose deterioration, where incorporation of suitable light absorbing materials not only does not slow down the process of deterioration but actually accelerates the decomposition.

The use of acetate film or cellulose ethers offers the possibility of diminishing the discoloration obtaining with exposure to light, since this is in major part associated with the nitro-content of nitrocellulose. The experiments just recorded suggest, however, that brittleness of such films will still occur on subjection to light action, any advantage which they might show being a function of their smaller light absorption. The observation by Dorée and Dyer[1] that cellulose, under the influence of ultra-violet light, is converted to oxycellulose with great loss of tensile strength is also evidence in support of this point of view.

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[1] C. Dorée and J. W. W. Dyer, "Some Effects of the Action of Ultra-violet Light on Cotton Fabrics," *Journal*, Soc. of Dyers and Colourists, Vol. 33, p. 17 (1917).

Photochemical Chain Reactions:

A fundamentally different set of conditions exists when the reaction initiated by light absorption is succeeded by a whole chain of thermal chemical reactions, a condition which is revealed by a considerable excess of molecules undergoing change per unit quantum of light energy absorbed, the quantum yield of the process. Under such conditions, the efficiency of any physical screening process is multiplied by a factor equal to the quantum yield of the light screened out. In addition, however, there exists a possibility of reducing the net change occurring, not by physical screening, but by suppression of the sequence of chemical processes succeeding the initial light absorption by incorporating an inhibitor in the material undergoing change. This development of the past twenty years involves so many reactions of both technical and scientific interest and has given so definite an orientation to the problem of prevention of deterioration that an extended treatment may be permitted.

Bodenstein[1] in 1913 pointed out that as many as 10^6 molecules of hydrogen chloride might be produced for every quantum of light energy absorbed by chlorine in admixture with hydrogen. He also emphasized that the yield was dependent on the purity of the gas mixture and could be markedly diminished by the presence of impurities such as oxygen, nitrogen-containing compounds such as ammonia, proteins and the like. His early efforts to formulate a chain or succession of reactions to account for the high yield from an initial light impulse were superseded by a mechanism postulated by Nernst in 1916:

$$Cl_2 + \text{Light} = 2\,Cl \quad \ldots\ldots \quad (a)$$
$$Cl + H_2 = HCl + H \quad \ldots\ldots \quad (b)$$
$$H + Cl_2 = HCl + Cl \quad \ldots\ldots \quad (c)$$

and so on by repetition of reactions (*b*) and (*c*). On such a basis inhibitors must act by destroying the H or Cl atoms which are the essential links in the chain. The Nernst mechanism still survives, at the present time, in spite of numerous doubts raised at intervals, as the best formulation of the hydrogen chloride chain.

The possible effectiveness of an inhibitor in such a reaction can easily be indicated. If, in a pure gas mixture, the chain reactions succeeding an initial light impulse were 10^6 in number, it is evident that the added agent which would interact with and remove from the system the first hydrogen atom formed in reaction (*b*) would reduce the hydrogen chloride yield 1,000,000 fold. A 100 per cent efficient trap for chlorine atoms in reaction (*a*) would suppress hydrogen chloride formation entirely. If it acted only on the chlorine atom produced in reaction (*c*) the yield would be reduced 500,000 fold. The earlier the inhibitor intervened in the reaction chain sequence the greater the proportionate reduction in reaction velocity and the greater its efficiency as an inhibitor. The longer the reaction chain, the greater the possible influence of an inhibitor in diminishing the reaction rate. The maximum reduction possible is to a rate equal to the reciprocal of the chain length.

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[1] M. Bodenstein, "A Theory of Photochemical Reaction Velocities," *Zeitschrift für physikalische Chemie*, Vol. 85, p. 329 (1913).

Chain Reactions and Retardation:

It was pointed out by Christiansen[1] that the existence of chain reactions whether initiated thermally or photochemically was indicated in all cases in which a minute amount of added material produces a marked diminution in reaction velocity. He pointed out that an inhibitor in small concentration could not affect either the collision factor, z, nor the activation energy or efficiency factor $e^{\frac{-E}{RT}}$ of Eq. 3. A chain mechanism of the type just discussed would, however, offer the possibility of such inhibitory power of a minute quantity of material, the inhibition being the more marked the longer the reaction chain, the efficiency of the inhibitor being determined by the stage in the chain at which it intervened, the earlier the more efficient. As we have already pointed out, a retardation might also be achieved by an inhibitor reducing the concentration of a powerful accelerator of reaction, which, in the case of reactions involving chains, might be spoken of as chain initiators. It will emerge that a distinction between these two possible modes of retardation can be achieved.

An ordered file of dominoes, arranged one behind the other at suitable intervals, provides a means of illustrating the concept of chain reactions. With the dominoes properly spaced an impulse communicated to the first will suffice to convert the whole row from the upright to the oblique position. It is the energy of the change which is the source of the activation energy of the succeeding change. Such initial impulses can be supplied by light energy, by ionization (alpha particles, electric discharges), by accelerators or catalysts or by an energetic collision between two energy-rich molecules. It is evident that in these last, the purely thermal processes, the velocity of reaction will be as many-fold, that calculated on the basis of collisions with a given energy of activation as there are chain members succeeding the initial activation process. Some thermal explosions are of this type. The intervention of an inhibitor in a reaction chain can be illustrated by the insertion of a rigid peg somewhere between the dominoes in a given row. If it intervenes early in the chain it represents a good inhibitor; if late, a poor one.

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[1] J. A. Christiansen, "Note on Negative Catalysis," *Journal of Physical Chemistry*, Vol. 28, p. 145 (1924).

Chain Processes in Autoxidation Chain Reactions:

That very many secondary chemical processes may succeed an initial activation, either by light or heat, even in liquid systems has been convincingly demonstrated by Bäckström[1] in cases of autoxidation such as the oxidation of sodium sulfite solutions and of aldehydes such as benzaldehyde. Bigelow[2] had long ago shown that the thermal oxidation of sulfite solutions was susceptible to inhibition and, as already stated, this was coupled by Titoff with the extraordinary sensitivity to acceleration by minute amounts of accelerating agents such as copper ions. The photochemical oxidation was found by Mathews and Dewey[3] and Mathews and Weeks[4] to be faster than the thermal reaction, and also inhibited by a variety of added agents. The chain character of the reaction followed from Bäckström's photochemical yield measurements, as many as 50,000 molecules of sodium sulfite reacting per absorbed quantum of light of wave length 2536.7 Å. even in 1-molar solutions. Bäckström established a link between the thermal and photochemical reactions by his observation that alcohols affect both rates of reaction alike, the relative rates in presence of such inhibitors being satisfactorily represented in both cases by the equation:

$$V = \frac{k_1}{k_2c + k_3}$$

where c is the concentration of inhibitor, the constants k_2 and k_3 being common to both thermal and photochemical reactions, k_1 varying according as the reaction was thermal or photochemical, being dependent on the rate of activation or formation of the initial stage in the chain process. The inhibitor constant, k_2, is specific for a given inhibitor. The presence of k_3 indicates the possibility of ending chains other than by an added inhibitor. Its importance diminishes the more important inhibition by the added inhibitor, k_2c, becomes.

Mechanism of Inhibitor Action:

The correctness of these general conclusions and the mechanism of inhibitor action in this particular case were established later by

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[1] H. L. J. Bäckström, "The Chain Reaction Theory of Negative Catalysis," *Journal*, Am. Chemical Soc., Vol. 49, p. 1460 (1927); *Meddelanden* från Kungligens Vetenskaps Akademiens Nobel Institut, Vol. 6, Nos. 15 and 16 (1927).

[2] S. L. Bigelow, "Catalytic Action on the Velocity of Oxidation of Sodium Sulphite by the Oxygen of the Air," *Zeitschrift für physikalische Chemie*, Vol. 26, p. 493 (1898).

[3] J. H. Mathews and L. H. Dewey, "The Production of Photochemically Active Rays in Ordinary Chemical Reactions," *Journal of Physical Chemistry*, Vol. 17, p. 230 (1913).

[4] J. H. Mathews and M. E. Weeks, "The Effect of Various Substances on the Photochemical Oxidation of Solutions of Sodium Sulphite," *Journal*, Am. Chemical Soc., Vol. 39, p. 635 (1917).

Alyea and Bäckström.[1] The inhibition involves an induced oxidation of the inhibiting alcohol, a molecule of the oxidation product (aldehyde or ketone) being formed whenever a chain is broken. The experimental results which support this conclusion may be summarized. At low alcohol inhibitor concentrations, the amount of alcohol oxidized increases with increasing alcohol concentration. At high inhibitor concentrations the amount of alcohol oxidized per unit time is constant, independent of its concentration, in both the thermal and photochemical reactions. In this latter concentration region, the number of inhibitor molecules oxidized per unit time is quantitatively the same for different alcohols of widely different inhibitory powers. Two alcohols present in a solution have an additive inhibitory effect and are oxidized in the ratio of their inhibitory powers; the total number of alcohol molecules oxidized is, however, the same as when only one alcohol is present. All these facts are explainable on the assumption that with sufficient alcohol present as inhibitor each chain process started is stopped by an alcohol molecule, the number of which molecules oxidized is a quantitative measure of the number of reaction chains initiated. Alyea and Bäckström showed that the number of secondary processes, the links in the chain, was the same in both thermal and photochemical reactions and is equal to the efficiency (molecules per quantum) as determined photochemically. They also found that copper sulfate accelerated the thermal reaction without altering the ratio of sulfite oxidized to alcohol oxidized. This means that the catalyst and inhibitor act independently. The catalyst initiates the chain process, the inhibitor quite independently breaks the chain of secondary reactions. The mechanism in this case was definitely not a case of inhibition by suppression of the concentration of a catalyst.

The autoxidations of many organic compounds show similar chain mechanisms. The oxidation of benzaldehyde and oenanthaldehyde were shown by Bäckström to be of this type. As many as 10,000 molecules of benzaldehyde were oxidized per quantum of light energy absorbed. As with sulfite solutions, these oxidations may also be accelerated by catalysts as, for example, manganese salts, though even benzaldehyde purified by many distillations in an atmosphere of carbon dioxide shows autoxidation.[2] Bäckström and Beatty[3] showed that, as in the case of sulfite, the inhibitory action was associated with an induced oxidation of the inhibitor, anthracene in the case studied. The primary oxidation product was anthranol which was autoxidizable, reacting with oxygen to give a peroxide which later slowly decomposed with the formation of the final reaction product anthraquinone. With increasing anthracene concentration the relative amounts of oxidation products formed approaches one mole of benzoic acid per mole of anthraquinone. The course of the reaction shows that the induced oxidation of the anthracene is the result of a reaction with a peroxide of benzaldehyde, but it may be shown that this reaction cannot be attributed to the stable form of this peroxide, benzoperacid. Side reactions occur also to minor degrees producing both anthrahydroquinone and also unidentified and complex colored products. The anthracene also plays the part of a screening material in the light reaction. These functions of anthracene are illuminating in view of the use of this reagent in the suppression of gum formation in cracked gasolines especially where these latter are exposed to light action in the visible-type gasoline stations.

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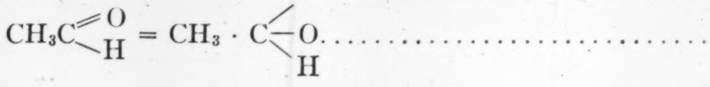
[1] H. N. Alyea and H. L. J. Bäckström, "The Inhibitive Action of Alcohols on the Oxidation of Sodium Sulphite," *Journal*, Am. Chemical Soc., Vol. 51, p. 90 (1929).

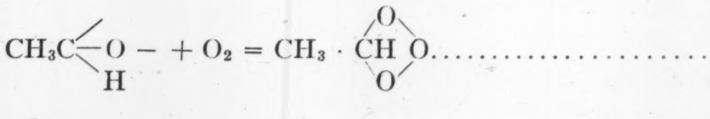
[2] H. J. Almquist and G. E. K. Branch, "The Absorption of Oxygen by Benzaldehyde," *Journal*, Am. Chemical Soc., Vol. 54, p. 2293 (1932).

[3] H. L. J. Bäckström and H. A. Beatty, "The Inhibitory Action of Anthracene in the Autoxidation of Benzaldehyde," *Journal of Physical Chemistry*, Vol. 35, p. 2530 (1931).

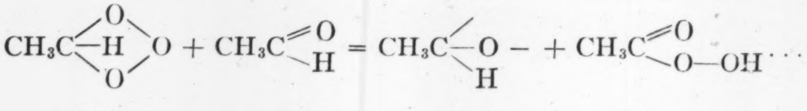
The unstable intermediate peroxide is also assumed by Bodenstein[1] to account for the kinetics of the oxidation of gaseous acetaldehyde, the kinetic treatment developed being also applicable to the oxidation of unsaturated hydrocarbons. The essential features of Bodenstein's mechanism are evident from the equations:



$$CH_3C{\begin{matrix}=O\\ \diagdown H\end{matrix}} = CH_3\cdot C{\begin{matrix}\diagup\\ -O\\ \diagdown H\end{matrix}} \quad (a)$$



$$CH_3C{\begin{matrix}\diagup\\ -O\ -\\ \diagdown H\end{matrix}} + O_2 = CH_3\cdot CH{\begin{matrix}\diagup O\diagdown\\ \quad O\\ \diagdown O\diagup\end{matrix}} \quad (b)$$



$$CH_3C{\begin{matrix}\diagup O\diagdown\\ -H\quad O\\ \diagdown O\diagup\end{matrix}} + CH_3C{\begin{matrix}=O\\ \diagdown H\end{matrix}} = CH_3C{\begin{matrix}\diagup\\ -O\ -\\ \diagdown H\end{matrix}} + CH_3C{\begin{matrix}=O\\ \diagdown O-OH\end{matrix}} \quad (c)$$

(A) (B) (C) (D)

Molecule (C) is assumed to be formed from molecule (A) and molecule (D) from molecule (B). In this way there results, through the reproduction of molecule (C) (the active molecule produced in reaction (a)), a chain mechanism without any necessity for assuming a transfer of the energy of activation which has been the difficulty in mechanisms obtaining in liquid systems.

Bodenstein also applied this mechanism to the elucidation of the kinetics of acetylene oxidation as studied by Spence and Kistiakowsky[2] and found a satisfactory interpretation of the experimental results. More recent data have led Spence[1] to a slight modification of the suggested mechanism which satisfactorily accounts for the observed products which include carbon monoxide, carbon dioxide, glyoxal, formaldehyde, formic acid and glycerosone, and also suggests a chain reaction with a chain length in wide vessels as long as 380. This latter was deduced from the influence of packing, which retards the rate of reaction, an influence first shown by Pease and Chesebro[2] for saturated hydrocarbons and by Hinshelwood and Thompson for hydrogen-oxygen explosions.[3] On the basis of chain mechanism the vessel walls terminate the chains which presumably involve radicals or atoms.

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[1] M. Bodenstein, "The Mechanism of the Oxidation of Acetalydehyde and Hydrocarbons," *Zeitschrift für physikalische Chemie*, Vol. 12, Abteilung B, p. 151 (1931).

[2] R. Spence and G. B. Kistiakowsky, "Kinetics of the Acetylene-Oxygen Reaction," *Journal*, Am. Chemical Soc., Vol. 52, p. 4837 (1930).

As amended by Spence, the Bodenstein mechanism is as follows:

$$C_2H_2 = C_2H_2' \tag{a}$$

$$C_2H_2' + O_2 = C_2H_2O_2'' \tag{b}$$

$$C_2H_2O_2'' + C_2H_2 = C_2H_2' + C_2H_2O_2' \tag{c}$$

$$C_2H_2O_2' + C_2H_2 = C_2H_2' + C_2H_2O_2 \tag{d}$$

$$C_2H_2O_2'' + O_2 = 2\,CO + H_2O_2 \tag{e}$$

$$C_2H_2O_2' + O_2 = CO + CO_2 + H_2O \tag{f}$$

$$C_2H_2O_2' = CO + H.CHO \tag{g}$$

$$2\,C_2H_2O_2' = CO + CHO.CO.CH_2OH \tag{h}$$

The intermediate product is assumed to exist in two forms $C_2H_2O_2''$ and $C_2H_2O_2'$ which represent different energy levels in the glyoxal system and whose successive degradation to glyoxal introduces the possibility of branched chains, a necessity in explosive reactions. The formic acid arises from interaction of formaldehyde and hydrogen peroxide since both formaldehyde and formic acid are quite stable at the temperature of 325° C. used in these studies of acetylene oxidation.

Spence points out that the experiments of Lenher[4] on the slow oxidation of ethylene show a close parallelism to the acetylene results. The reaction has an induction period, is strongly inhibited in packed vessels, and in open vessels the rate is determined by the nature of the wall. A feature of Lenher's experiments which indicates the close relationship which these reactions bear to the problem of preservation against deterioration is to be found in the fact noted by Lenher that polymerization of ethylene is much accelerated by the presence of small amounts of oxygen in the system. Oxidation of the hydrocarbon induces marked polymerization of the ethylene. This fact in itself is evidence of a chain mechanism for the process. It is paralleled by a number of analogous polymerizations which are induced by oxidation and are susceptible to the retarding influence of inhibitors.

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[1] R. Spence, "The Slow Combustion of Acetylene," *Journal*, Chemical Soc. (London), Vol. 1932, p. 686 (1932).

[2] R. N. Pease, "Characteristics of the Non-Explosive Oxidation of the Propanes and Butanes," *Journal* Am. Chemical Soc., Vol. 51, p. 1839 (1929).

[3] C. N. Hinshelwood and H. W. Thompson, "Kinetics of the Reaction Between Hydrogen and Oxygen, *Proceedings*, Royal Soc., A, Vol. 118, p. 170 (1928).

[4] S. Lenher, "The Reaction Between Oxygen and Ethylene," *Journal*, Am. Chemical Soc., Vol. 53, p. 3737 (1931).

Polymerization as a Chain Reaction:

The earliest researches of Moureu and Dufraisse[1] on the subject of prevention of deterioration were concerned with the stabilization of acrolein against polymerization. They found that this polymerization was greatly accelerated by traces of oxygen and also by exposure to light and that both processes were inhibited by a variety of substances, notably hydroquinone. These authors[2] showed that, even in absence of oxygen, light alone accelerated the formation of disacryl, shortening the reaction time from a year or more to a few seconds in strong sunshine. Furthermore, with such precautions against the absence of oxygen, hydroquinone increased the time of first observation of disacryl from 12 minutes (no hydroquinone) to more than 18 hours (1 per cent hydroquinone). These results indicate an accelerated polymerization by reason of an oxidation reaction, an association of reactions already emphasized by Engler and Weissberg[3] in their classical researches on autoxidation, but also the possibility of its initiation by light alone and the inhibition of the purely polymerization process by added agents.

Bäckström[4] in his experimental confirmation of the Christiansen chain reaction theory of inhibition cites these data of Moureu and Dufraisse as indicating that the polymerization reactions have chain characteristics similar to those of the autoxidation processes and that, in absence of oxygen, the inhibition process must involve "photochemical" reactions between active molecules of the reactant and the inhibitor. These side-reactions he described as "photochemical" because they involved energy-rich molecules which could be obtained either by reaction (including oxidation and polymerization) or by light absorption. It had already been pointed out by Taylor[5] that compound formation between reactant and inhibitor was often a characteristic of inhibited reactions and that an inhibitor acting in such manner would be particularly powerful since it would remove the active substrate molecules in competition with the oxygen, which is present only in very low concentration.

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[1] C. Moureu and C. Dufraisse, "On Antioxidants," *Comptes Rendus* de l'Academie des Sciences (Paris), Vol. 169, p. 705 (1919); Vol. 174, p. 258 (1922); *Bulletin* de la Société Chimique de France, Vol. 31, Series 4, pp. 224, 1152 (1922); Vol. 35, Series 4, p. 1564 (1924).

[2] C. Moureu and C. Dufraisse, "Autoxidation and Antioxidants," *Bulletin* de la Société Chimique de France, Vol. 35, Series 4, p. 1564 (1924).

[3] C. Engler and J. Weissberg, "Kritische Studien über die Vorgänge der Autoxydation," p. 179, Braunschweig (1904), which discusses induced autopolymerisation of styrol, cyclopentadiene, indene, cumarone, and certain petroleum hydrocarbons.

[4] H. L. J. Bäckström, "The Chain Reaction Theory of Negative Catalysis," *Meddelanden* från Kungligens Vetenskaps Akademiens Nobel Institut, Vol. 16, No. 6, p. 16 (1927).

[5] H. S. Taylor, "The Problem of Negative Catalysis," *Journal of Physical Chemistry*, Vol. 27, p. 322 (1923).

That such polymerization processes belong to the class of chain reactions is definitely indicated by the work of Starkweather and G. B. Taylor[1] on the kinetics of thermal polymerization of vinyl acetate alone or in solution and by the photochemical studies of H. S. Taylor and Vernon[2] on the polymerization of both vinyl acetate and styrene. In this latter work it was shown that a quantum of light energy was capable of producing the polymerization of as many as 1000 molecules of vinyl acetate. The polymerization of these vinyl compounds is enormously susceptible both to acceleration and retardation. Oxygen and peroxides are catalysts. Anti-oxidants such as sulfur, hydroquinone, etc., are powerful inhibitors. An extended study of comparative efficiencies of such inhibitors has recently been made by Alyea and Jeu[3] for the photo-polymerization of vinyl acetate. Hydroquinone, pyrocatechol and especially pyrogallol have pronounced efficiencies. A comparison of the efficiencies thus obtained with those in sulfite oxidation suggests to Alyea and Jeu that the inhibitor is acting to stop an oxidation reaction, the assumption being made that the photo-polymerization of vinyl acetate requires the presence of a small amount of oxygen. Excess oxygen in the photo-polymerization of vinyl acetate was shown by Taylor and Vernon to prevent polymerization. On the other hand Conant and Peterson[4] have claimed that traces of peroxide are essential to polymerization of isoprene and n-butyraldehyde under pressure. As has been already mentioned it must, however, be borne in mind that the work of Moureu and Dufraisse with acrolein indicates a powerful photo-polymerization with careful regard to absence of oxygen in the system.

Alyea and Jeu have devised a new method of determining chain length based on their kinetic studies of rates of reaction for first order reactions in presence of inhibitors. Their general equation is:

$$\frac{2.3}{t}\log\frac{1}{1-x} = \frac{K}{k_2 + kC}$$

where x is the fraction reacting in time t; K is composite of the number of chains initiated at $t = 0$ and the probability of continuing the chains; $k_2 + kC$ is the probability of breaking the chains by a constant factor k_2 (wall or impurity), or by an inhibitor of concentration C and inhibitory power k. Alyea and Jeu show that a determination of the values of K and k_2 permits a deduction of probable chain lengths from the values of k_2. In this way they find chain lengths in good agreement with the results of photochemical studies. For dilute solutions of vinyl acetate they find a polymerization chain length approximating 2500.

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[1] H. W. Starkweather and G. B. Taylor, "The Kinetics of the Polymerisation of Vinyl Acetate," *Journal*, Am. Chemical Soc., Vol. 52, p. 4708 (1930).

[2] H. S. Taylor and A. A. Vernon, "The Photo-polymerisation of Styrene and Vinyl Acetate," *Journal*, Am. Chemical Soc., Vol. 53, p. 2527 (1931).

[3] K. K. Jeu, "Comparative Inhibitory Powers of Organic Substances in Chain Reactions," Thesis, Princeton (1932).

[4] J. B. Conant and C. O. Tongberg, "Polymerisation Reactions Under High Pressure," *Journal*, Am. Chemical Soc., Vol. 52, p. 1659 (1930); J. B. Conant and W. R. Peterson, "Polymerisation Reactions Under High Pressure II," *Journal*, Am. Chemical Soc., Vol. 54, p. 628 (1932).

The polymerization of dienes is similarly sensitive to catalysts, light and inhibitors, so that these cases may also be reckoned among the chain reactions. Butadiene and isoprene polymerize less readily than the vinyl compounds but they are sensitive to oxygen, ozonides, peroxides. It is of interest also to record that chloroprene, $CH_2 = C(Cl) - CH = CH_2$, is sensitive in its polymerization[1] to similar catalysts, to light, pressure and to inhibitors. In the presence of 1.6 per cent thiodiphenylamine and in presence of air the chloroprene was still fluid after 13 months in contrast to the 1 to 8 days required with peroxide or air alone as catalysts. Aromatic nitro compounds, notably trinitrobenzene, were notable members of the class of inhibitors for chloroprene. The formation of increased amounts of solid polymer, as an after effect in the dark, after a preliminary illumination of the chloroprene vapor is the best possible evidence of a chain mechanism for this polymerization. The product is designated as the ω-polymer and is regarded by Carothers as a cross-linked chain polymer.

Chain Mechanism in Decomposition Processes:

The outstanding example of a decomposition reaction for which a chain mechanism has been demonstrated is the decomposition of hydrogen peroxide solutions. The effect, as light screens, of added substances has already been emphasized but the greater efficiency of such substances when in the peroxide solution as compared with their effect when outside the peroxide has to be associated with the existence of a chain mechanism. Various substances, such as ethyl alcohol and ethylamine, sodium hydroxide, etc., which exert no influence as screens have nevertheless marked inhibitory powers even in minute concentrations on the photo-decomposition process. This is evidence, on the Christiansen theory, of a chain mechanism and a quantitative study of the reaction bears this out. Kornfeld[2] found that, in dilute solutions, up to 0.5 molar, the quantum yield, peroxide molecules decomposed per light quantum absorbed increased steadily to as much as 80 molecules/$h\nu$. The more comprehensive investigations of Allmand and Style[1] indicate even longer chains, dependent in length on the concentration of peroxide with a maximum between .1 and 2 moles per liter. The quantum yield in this region reached as high as 400 molecules per absorbed quantum at 21° C. varying with the wave length employed. Allmand and Style determined the temperature-coefficient of the reaction for three wave lengths 3650, 3070 and 2750 Å. and found that the temperature coefficients were 1.42, 1.38 and 1.28 per 10° C., respectively, independent of peroxide concentration. This dependence of the temperature coefficient on wave length suggests a possibility of considerable interest to those interested in the discovery of chain reactions by photochemical studies. The decreasing temperature coefficient with increasing frequency strongly suggests that the temperature effect is concerned with the primary process. On a theory put forward by Tolman,[2] the activation energy calculated from such coefficients should represent the excess energy, over the average energy of all the molecules, required by an absorbing molecule in order that the absorption process shall initiate a reaction sequence. It was calculated by Allmand and Style that, on this assumption, with the coefficients observed, only a small fraction ($< 10^{-4}$) of all the absorbing molecules would react subsequent to absorption, and that, therefore, the chain length instead of being about 10^2 to 10^3 might actually be 10^4 to 10^7 links long. Such a chain length would be in good agreement with observed variations in the inhibitory powers of added substances as recently studied by Alyea and Jeu. They found that on the basis of pyrogallol as standard and equal to 3200 the inhibitory power of ethylamine was 20,300, phenol 11,300, hydroquinone 8400, ethyl alcohol 130, with acetamide only 33. Such varied inhibitory powers suggest chains 10^4 long or greater.

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[1] W. H. Carothers, I. Williams, A. M. Collins, and J. E. Kirby, "Acetylene Polymers and Their Derivatives II; A New Synthetic Rubber; Chloroprene and Its Polymers," *Journal*, Am. Chemical Soc., Vol. 53, p. 4203 (1931).

[2] G. Kornfeld, "The Decomposition of Hydrogen Peroxide in Ultra-violet Light," *Zeitschrift für Wissenschaftliche Photographie*, Vol. 21, p. 66 (1921).

It might, therefore, be pertinent to offer this general observation. Quantum yields much greater than unity are definite photochemical evidence of the existence of chains. It may, however, arise that actual chain reactions show low quantum yields; in such circumstances only a fraction of the absorbed quanta initiate chains. As a corollary the quantum yield of the photo-process is a measure of the minimum chain length.

Allmand and Style showed that the decomposition of the peroxide solutions was, under certain conditions of concentration and wave length, proportional to the square root of the intensity of absorbed light. Such a relation to the light intensity is normally an index of the production of a photo-catalyst which subsequently disappears by a recombination process involving two of the species.[1] For this particular reaction Allmand and Style suggest two possible primary reactions:

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[1] A. J. Allmand and D. W. G. Style, "The Photolysis of Aqueous Hydrogen Peroxide Solutions," *Journal*, Chemical Soc. (London), p. 596 (1930).

[2] R. C. Tolman, "The Temperature Coefficient of Photochemical Reaction Rate," *Journal*, Am. Chemical Soc., Vol. 45, p. 2285 (1923).

$$H_2O_2 + h\nu = 2\,OH \tag{a}$$

$$\text{or } H_2O_2 + h\nu = H_2O + O \tag{b}$$

with the two possible recombination processes

$$2\,OH = H_2O_2 \text{ or } H_2 + O_2 \tag{c}$$

$$\text{or } 2\,O = O_2 \tag{d}$$

Reaction (*a*) is the reaction process suggested by the nature of the absorption spectrum as studied by Urey, Dawsey and Rice.[2] With such a primary process a chain mechanism similar to one suggested by Haber and Willstätter[3] for the decomposition of peroxide by the enzyme catalase. It may be formulated thus:

$$H_2O_2 + h\nu = 2\,OH \tag{f}$$

$$OH + H_2O_2 = H_2O + O_2H \tag{g}$$

$$O_2H + H_2O_2 = H_2O + O_2 + OH \tag{h}$$

This latter reaction (*h*) may be better understood if written in two stages:

$$O_2H = H + O_2 \tag{h_1}$$

$$H + H_2O_2 = H_2O + OH \tag{h_2}$$

In the enzyme reaction Haber and Willstätter start the reaction chain at reaction (*h*) by the enzyme reaction:

$$\text{Catalase} + H_2O_2 = \text{Desoxy-catalase} + HO_2$$

In both types of chains the OH radical is the active link in the chains. The radical O_2H is a familiar radical in the intermediate stages of the hydrogen-oxygen reaction initiated by H atoms.[4] The chains would on this basis be ended by the reaction (*c*) above or by reaction of either HO_2 or OH with the added inhibitor. In spite of much work already achieved with this simple process, much still remains to be accomplished before the problems of mechanism are finally solved.

With hypochlorites, the photochemical evidence for chains is not so positive. The best studies by Allmand and his colleagues[5] indicate quantum yield in the neighborhood of 1 to 3. There are certain results which do, however, indicate chains. The temperature coefficient of the $Cl.H_2O$ photolysis has a value of 1.4,[1] which at 20° higher temperatures than those employed by Allmand would give quantum yields considerably greater than 3, the maximum attainable without a chain mechanism. Further, for NaOCl solutions with a wave length of 2536 Å., Allmand and Webb found a value of 4.7 again in excess of the maximum non-chain possibility of 3.

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[1] G. B. Kistiakowsky, "Photochemical Processes," p. 96, Chemical Catalog Co., New York City (1928).

[2] H. C. Urey, L. H. Dawsey and F. O. Rice, "The Absorption Spectrum and Decomposition of Hydrogen Peroxide by Light," *Journal*, Am. Chemical Soc., Vol. 51, p. 1371 (1929).

[3] F. Haber and R. Willstätter, "Unpaired Electrons and Radical Chains in the Reaction Mechanism of Organic and Enzymic Changes," *Berichte* der Deutschen Chemischen Gesellschaft, Vol. 64, p. 2844 (1932).

[4] H. S. Taylor, "Photosensitisation and the Mechanism of Chemical Reactions," *Transactions*, Faraday Soc., Vol. 21, p. 560 (1925); also J. R. Bates, D. J. Salley, H. S. Taylor and G. I. Lavin. Forthcoming papers in *Journal*, Am. Chemical Soc., December, 1932.

[5] A. J. Allmand, P. W. Cunliffe and R. E. W. Maddison, "The Photodecomposition of Chlorine Water and of Aqueous Hypochlorous Acid Solutions, Part I," *Journal*, Chemical Soc. (London), Vol. 127, p. 822 (1925); Part II, *Ibid.*, Vol. 131, p. 655 (1927); A. J. Allmand and W. W. Webb, "The Photolysis of Sodium Hypochlorite Solutions," *Zeitschrift für physikalische Chemie*, Vol. 131, p. 189 (1928).

Quite recently Kauffmann[2] has cited chemical evidence pointing to a chain mechanism in hypochlorite decomposition. Bleach liquors may be activated by a variety of added agents such as hydrogen peroxide, hydrazine, ammonia and formaldehyde. In the presence of such agents the bleach liquors show an enhanced oxidation activity towards dyes and other substrates such as cellulose. The discharge of the color of an Orange II dye which, with a given bleach liquor, may take 15 minutes, occurs practically instantaneously on addition of 1 ml. of 3-per-cent hydrogen peroxide to 100 ml. of the bleach liquor. That the action is not due to nascent oxygen from the peroxide is evident since hydrazine and ammonia act as activators. Kaufmann employs the Haber-Willstätter theory to provide a mechanism for the process the first stage of which, as in the sulfite oxidation, consists in an ionic reaction producing a free radical:[3]

$$ClO' + Cu^{\cdot\cdot} = ClO + Cu^{\cdot}$$

In alkaline solutions a radical chain involving hydroxyl is thereby set up according to the equations:

$$ClO + ClO' + OH' = 2\,Cl' + O_2 + OH$$
$$OH + ClO' = ClO + OH'$$

On this basis the activators are substances yielding hydroxyl in the liquid. Thus, with peroxide:

$$H_2O_2 + ClO' = HO_2 + Cl' + OH$$

and possibly

$$HO_2 + ClO' = Cl' + OH + O_2$$

The higher oxidation activity of the bleach liquors containing activators is associated by Kaufmann with the hydroxyl concentration thus produced and maintained by a chain mechanism, even in the oxidation of the substrate. Thus, if this latter be represented by the formula RH_2 the following reaction chain sequence is possible:

$$RH_2 + OH = RH + H_2O$$
$$RH + ClO' = R + Cl' + OH$$

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[1] A. Benrath and E. Hertel, "The Photochlorination of Aliphatic Compounds in Carbon Tetrachloride," *Zeitschrift für Wissenschaftliche Photographie*, Vol. 23, p. 30 (1924).

[2] H. Kauffmann, "Reaction Chains in Oxidation Processes, *Berichte* der Deutschen Chemischen Gesellschaft, Vol. 64, p. 179 (1932).

[3] F. Haber and R. Willstätter, "Unpaired Electrons and Radical Chains in the Reaction Mechanism of Organic and Enzymic Changes," *Berichte* der Deutschen Chemischen Gesellschaft, Vol. 64, p 2844 (1932).

In pure hypochlorites, containing no catalyst or activator, the reaction:

$$HClO + ClO' = ClO + Cl' + OH$$

is a mechanism whereby the small activity of pure bleach liquors can arise. It is in agreement with this concept that the maximum activity of such liquors obtains at about pH = 8, the equation indicating that both hypochlorite and ion are necessary to produce the reaction chain. Also the order of reaction for decomposition of such liquors should be second order and dependent on alkali concentration —a fact known empirically for some years.[1]

APPLICATIONS

It will not be possible to present any extended development of applications of the principles already discussed. Such a presentation, if comprehensive, would occupy a volume in itself. Rather it is the aim in the succeeding paragraphs to indicate briefly, by particular examples, the practical importance of the fundamentals under discussion in such manner that application to other materials may be undertaken with adequate comprehension of the scientific factors involved.

Rubber:

The case of rubber is one in which conspicuous success has attended the application of the principles herein outlined. The aging of rubber, whereby it becomes hard and brittle, the development of cracks and loss of resistance to abrasion, the development, too, of stickiness in rubberized materials are all familiar phenomena. It is readily shown that the deterioration is due to the oxygen of the air, to light action or to both. The oxygen adds to the double bonds in the molecular structure and also promotes a decomposition of the rubber molecule, the latter continuing after the first is complete. The oxygen absorption curves are auto-accelerating in nature. During the course of the absorption the rubber first becomes tacky, then the tackiness disappears and it becomes weak. Finally it becomes hard and brittle. The tackiness occurs at 80° C. after absorbing only 0.02 to 0.05 mole of oxygen per $C_{10}H_{16}$ unit. After approximately 0.5 mole is absorbed the tackiness disappears and hardness and brittleness is reached after 1.0 mole is absorbed per $C_{10}H_{16}$ unit. The tensile strength shows a tremendous change as a result of oxygen absorption. Absorption of oxygen equal to 0.5 per cent decreases the tensile strength by nearly 50 per cent, the diminution in strength being directly proportional to oxygen absorption over the range 0 to 1 per cent.

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[1] H. Kauffmann, "Bleach Liquors and Bleach Reactions," *Zeitschrift für angewandte Chemie*, Vol. 27, p. 364 (1924).

It is significant that the oxygen absorption is dependent on the curing process. The rate of oxygen absorption for raw rubber is less than that for cured rubber and increases with the degree of cure, facts in agreement with observations on the natural aging of cured rubber. Over-curing increases the rate of absorption of oxygen. It is certain, however, that the effect of oxygen on rubbers of different degrees of cure is not the same in all cases; the system is complex. The oxygen absorption and also the aging qualities of rubber are profoundly modified by incorporating in the rubber small amounts of chemicals known as antioxidants, anti-agers or age-resistants. A wide variety of organic compounds is now in use for this purpose and has produced an important auxiliary chemical industry and a material improvement in the quality of rubber goods. Condensation products of aliphatic aldehydes and aromatic amines of various degrees of substitution are important members of this group of substances. It has been established that their influence is exercised on the rate of oxygen absorption; they materially reduce the rate of oxygen absorption, normally the more effectively the greater the concentration and dependent to a major degree on the constitution of the added inhibitor. They, therefore, behave analogously to the inhibitors of oxidation processes already discussed. The detailed interpretation of their action is naturally much more difficult than in the case of the simpler oxidizable compounds discussed in the theoretical portion of this work. There is evidence that raw rubber itself contains natural inhibitors of oxidation; hence the slow oxidation found with such material.[1]

As might be expected, deterioration is also sensitive to acceleration by catalysts and, as an example, the case of copper stearate may be cited. This substance is a vigorous accelerator of deterioration due to oxidation. Jones and Craig[2] show that antioxidants bring about a retardation of deterioration in the presence of the copper accelerator roughly in the order of their efficiencies in absence of copper, the actual rates of deterioration being much greater, however, when copper was present than when absent. The presence of copper did not change the type of curve obtained with varying amounts of the inhibitor phenyl-β-naphthylamine, which, in presence and absence of copper, did not markedly influence the rate of deterioration when present in concentrations beyond about 1 per cent inhibitor. The research shows that the catalyst and inhibitor each exercises its normal functions and that together they tend to neutralize the effect due to each. The possible catalytic effects of added materials is a matter of importance in the choice of pigments to be compounded with rubber.

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[1] For literature survey and oxygen absorption studies, see G. T. Kohman, "The Absorption of Oxygen by Rubber," *Journal of Physical Chemistry*, Vol. 33, p. 226 (1929).

[2] P. C. Jones and D. Craig, "Behavior of Antioxidants in Rubber Stocks Containing Copper," *Industrial and Engineering Chemistry*, Vol. 23, p. 23 (1931).

Experience shows also the importance of light in this case. It undoubtedly speeds up the reactions involved.[1]

Hydrocarbons:

The problem of deterioration in respect to hydrocarbons includes the keeping qualities of gasoline and transformer oils. In the former case the problem has recently become more acute by reason of the greater production of cracked gasolines with a relatively high concentration of unsaturateds with especial emphasis on the presence of diolefines. The tendency to gum formation in gasolines is due mainly to the diolefines although the simple ethylenes may form gum on extended oxidation. Kogerman[2] showed recently that 2–4 hexa and pentadiene absorb 2 moles of oxygen per pair of double bonds yielding compounds similar to the gums obtained in cracked gasoline. It is well known that absorption of oxygen is a preliminary stage in the development of gumminess in such gasolines and the rate of absorption is of the now-familiar auto-accelerative type accompanied by the accumulation of peroxides. There is a preliminary induction period during which, undoubtedly, inhibitors, probably of a phenolic nature, present in the natural materials, are performing their function as retarding agents. Peroxides added initially to the gasoline eliminate the induction period presumably through oxidation of the inhibitors. The natural inhibitors may be removed by alkali washes whereupon, again, the induction period is shortened. The interaction of added peroxides with inhibitors, destroying these latter, is not without its important practical significance in the technique of inhibitor addition. It suggests that, for maximum inhibitor efficiency, the gasolines to which they are added should be as substantially free from peroxides as practical. Otherwise the inhibitors will be readily removed by oxidation and their retardation efficiency destroyed. The high temperatures of cracking distillations are generally sufficient to decompose any peroxides present so that a freshly distilled cracked gasoline should be substantially free from peroxides. It is at such a stage that maximum inhibitor efficiency may be obtained. The lower temperatures of straight distillation may not be high enough to decompose peroxides which may, therefore, be carried over. These should be removed prior to inhibitor addition for maximum efficiency of the latter.

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[1] A. R. Kemp, W. S. Bishop and P. A. Lasselle, "Oxidation Studies of Rubber, Gutta-Percha, and Balata Hydrocarbons," *Industrial and Engineering Chemistry*, Vol. 23, p. 1444 (1931).

[2] P. N. Kogerman, "The Autoxidation of Diolefins and Their Relation to Gum-Formation in Cracked Gasoline, *Transactions*, Second World Power Conference (Berlin), Vol. 8, p. 33 (1930).

There is definite evidence[1] that most, if not all, of the residue left when gummy gasoline is evaporated is formed from peroxides during the evaporation. It is this fact that makes the problem of gum prevention a problem of inhibition of oxidation. Of inhibitors a large patent literature exists, as examples of which, the following may be cited: hydroquinone, anthracene, acetanilide, phenol, methylaminophenol and the corresponding benzyl derivative.

Refined transformer oil is mainly composed of saturated hydrocarbons with a less tendency to oxidation than oils containing unsaturated hydrocarbons capable of forming peroxides. Nevertheless, oxidation of the saturated hydrocarbons does occur even at ordinary temperatures and this oxidation is greatly accelerated by catalytic materials. Copper, iron, lead, manganese and cobalt soaps are powerful accelerants of such oxidations. Preservation of these oils from deterioration resolves itself in part, therefore, into attempts to keep the concentration of such accelerants down to a minimum. With the metal containers and equipment necessary in the use of such oils, attention must, therefore, be paid to the presence of acidic constituents in the oil, since these will attack metals and their oxides yielding the accelerant soaps. Quite recently the use of selenium and sulfur in such oils as well as organic sulfides such as isoamyl sulfide has been shown to diminish the oxidation of transformer oils.[2] More sludge is formed with sulfur in the oil than without, and these authors indicate that heavy sludge forming oils contain certain amounts of sulfur and unsaturated compounds, both necessary for sludge formation in their view.

It is known that light accelerates the decomposition processes occurring in such oils. Also, the effect of the electric fields present in such oils in use is an item of importance in their stability. As is well known, these fields produce decomposition of hydrocarbons into fragments which then have further possibilities of reaction. It is these latter reactions in which the possibility of a chain mechanism most prominently arises and against which the utilization of inhibitors may be invoked. A number of patent applications is concerned with the stabilization of transformer oils against the action of air, light and electrical action. Hydroxybiphenyls have been proposed for such purposes.[3]

The development of antiknock gasolines is in reality the prevention, by blending of suitable hydrocarbon mixtures or by addition of suitable antioxidant materials, of a premature deterioration of hydrocarbons under the temperature-pressure conditions obtaining in the internal combustion engine. The reactions occurring are characteristically chain reactions. An extended treatment of this familiar field is impossible in the present survey.

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[1] J. A. C. Yule and C. P. Wilson, Jr., "Peroxides and Gum in Gasoline," *Industrial and Engineering Chemistry*, Vol. 23, p. 1254 (1931).

[2] S. Mizushima and T. Yamada, "The Antioxygenic Effects of Sulphur and Selenium upon Refined Transformer Oil and Paraffin Wax," *Journal*, Soc. Chemical Industry of Japan, Vol, 32, p. 848 (1929); "Influence of the Added Sulphur on the Oxidation of Less Refined Transformer Oils," *Journal*, Soc. Chemical Industry of Japan, Vol. 32, p. 316 (supplemental binding) (1929).

[3] United States Patent No. 1,784,359 to C. F. Kaegebehn.

Fats and Oils:

Observations of suppression of rancidity and oxidation of oils date back well into the first half of the nineteenth century. Moureu and Dufraisse call attention to the observation of Deschamps in 1843 that fresh lard containing gum benzoin or populin did not become rancid as did pure lard. Moureu and Dufraisse attribute this to the antioxygenic activity of the benzoin and saligenin contents of the added agents. Oak wood was shown by Chevreul in 1856 to inhibit the drying of linseed oil; poplar and pine wood showed the same phenomenon in less degree. Moureu and Dufraisse ascribe this to the presence of tannin in the woods. They themselves included linseed oil, nut oil and butter in the list of substances for which they demonstrated the effect of inhibition of oxidation. The phenomenon is, therefore, of importance in the field of paints and varnish, in the artificial leather industry (nitrocellulose-castor oil films) in the field of pharmaceuticals (cod-liver oil) and in the edible oil industry (beef fat, butter, lard).

The drying of oils is, in large part, an oxidation process very sensitive to positive catalysts (driers, lead, cobalt, manganese soaps, etc.) and to the accelerating action of light. Oxygen is absorbed at rates auto-accelerative in nature, the induction period being a function of the amount of accelerators present and dependent, in the absence of these, on the amount of natural inhibitors present. A variety of antioxidants prolong the induction period greatly. It is evident that these antioxidants are consumed in minimizing oxidation of the oil for, after an induction period due to added inhibitors, the rate of oxygen absorption is substantially what it would have been without the intervening induction period. It was shown by Rogers and Taylor[1] that the drier and inhibitor apparently act independently of each other in a manner consistent with the view that the drier starts reaction chains and the inhibitor breaks chains, itself being oxidized. Consistent with such oxidation of the inhibitor are also the observations of Wagner and Brier[2] that inhibitor added after the termination of the induction period at 100° C. is not effective as an antioxidant. At 30° C. it is effective in inverse ratio to the rate of oxidation. Both facts point to a removal of inhibitor by oxidation due to accumulation of peroxide in the oxidizing material. The addition of partially oxidized linseed oil to a system which normally undergoes an induction period shortens the induction period to an extent directly proportional to the amount of addition, a fact also pointing to consumption of inhibitor.

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[1] W. Rogers and H. S. Taylor, "The Rate of Oxidation of Linseed Oil," *Journal of Physical Chemistry*, Vol. 30, p. 1334 (1926).

[2] A. M. Wagner and J. C. Brier, "Influence of Antioxidants on the Rate of Oxidation of Linseed Oil, Parts I and II," *Industrial and Engineering Chemistry*, Vol. 23, pp. 40, 662 (1931).

The utilization of inhibitors for the protection of paint and varnish films thus stumbles on the difficulty that the process which produces the film is retarded by materials which might be added to the mixture to protect against subsequent deterioration the films produced; and also the drying process itself destroys such added preservatives. Hence it would seem that the only available possibility in the case of paints and varnishes is that proposed by Scheiber,[1] of applying to a finished coat of paint an additional coat of inhibitor dissolved in a suitable solvent which would permeate to a degree the paint vehicle. In paints of the nitrocellulose type which do not involve a "drying" process, but only solvent evaporation, a wider scope for the use of inhibitors is possible.

Since many pigments are accelerative of oxidation processes, a positive control of deterioration in paints and varnishes can be obtained by due attention to the pigments used. Especial care should be exercised to see that, so far as possible, inert, non-oxidative pigments are employed. A material improvement in paint film life can thereby often be secured.

With compositions containing non-drying oils, which are, however, subject to oxidation processes, a more positive effect can be secured from the use of inhibitors. Thus, as shown by Rigakusi,[2] the oxidation of castor oil is markedly diminished by the presence of such agents as diphenylhydrazine and α-naphthylamine. One may, therefore, expect beneficial effects from such materials in nitrocellulose-castor oil films present in artificial leather and consequent protection of such against the aging common to such materials. Also, with such materials, the absence of oxidative pigments is also desirable in the interests of durability.

Light, heat and inorganic salts such as those of copper are powerful accelerants of the oxidation of butter and lard.[3] The effect of gum benzoin and saligenin as inhibitors of such oxidation has already been mentioned. Vibrans[4] has recently indicated that 0.5 per cent of diphenyl ethylenediamine or 0.2 per cent of thymol are preventives of rancidity in vegetable oils. Similar considerations apply to pharmaceuticals such as cod-liver oil.

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[1] J. Scheiber, "The Importance of Negative Catalysis in the Varnish Industry," *Farbe und Lack*, p. 26 (1927).

[2] B. Y. Rigakusi, "The Action of Antioxidants on the Oxidation of Fatty Oils," *Bulletin des Matieres Grasses* de L'Institut Colonial de Marseille, Vol. 15, p. 65 (1931).

[3] K. E. Wright and O. R. Overman, "The Action of Copper, of Lactic Acid, and of the Temperature on the Autoxidation of the Fatty Material of Butter and Lard," Lait, Vol. 11, p. 563 (1931); C. H. Lea, "Effect of Light on Oxidation of Fats," *Proceedings*, Royal Soc. (London), B, Vol. 108, p. 175 (1931); H. A. Mattill, "Antioxidants and the Oxidation of Fats," *Journal of Biological Chemistry*, Vol. 90, p. 141 (1931).

[4] F. C. Vibrans, "Antioxidants in Edible Oil Preservation," *Oil and Fat Industry*, Vol. 8, pp. 223, 227, 263, 277 (1931).

Ethers and Essential Oils:

It has long been known that ethers formed peroxidic products in contact with air and that light and catalysts accelerated the oxidation process. Milas[1] has recently shown that in addition to the accelerative action of light and metals there is an inhibitory action by such substances as iodine, picric acid and benzoquinone. Delepine[2] had earlier shown that a variety of thio-ethers oxidize with accompanying chemiluminescent effects (a criterion, according to Bäckström, of a chain mechanism) and that ether, ethylene oxide, turpentine, ethyl and methyl alcohols, benzene, etc., diminish the oxidation process.

Milas[3] has also made extended studies of autoxidation phenomena, inhibited by added agents, with a variety of essential oils.

Textiles and Cellulose:

Sisley and Seyewetz[4] have claimed the protection of silk against light, heat and atmospheric action by means of thiourea, hydroquinone and their derivatives. Similar studies with other textiles would be advantageous. Dye-stuffs such as azo-dyes and eosin are apparently protected against light action by inhibitors. The deterioration of textiles and paper by aging and by light action is well known although the importance of the various factors involved has not been decisively settled. Undoubtedly, attention should be paid to the effects of inorganic constituents, such as alkalis and iron compounds, present in the ash since it is known that such agents have enormously positive accelerating effects on the autoxidation of analogous compounds such as the polyhydroxy alcohols.[5] The oxidation of such materials also by reagents employed in bleaching processes is also pertinent to the problem on hand.[6]

Enough has been cited by way of exemplification to show that the problem of deterioration in a wide variety of important products is one to which the fundamentals laid down in the preceding sections are eminently applicable and, therefore, warrants, by those concerned, a systematic and scientific investigation for eventual solution.

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[1] N. A. Milas, "The Mechanism of the Autoxidation of Certain Ethers," *Journal*, Am. Chemical Soc., Vol. 53, p. 221 (1931); with literature references to earlier work and mechanisms involved.

[2] M. Delepine, "The Autoxidation of Organic Sulphur Compounds," *Bulletin* de la Société Chimique de France, Vol. 31, Series 4, p. 762 (1922); *Bulletin* de la Société Chimique Belgique, Vol. 33, p. 339 (1924).

[3] See, for example, N. A. Milas, "Autoxidation," *Chemical Review*, Vol. 10, p. 295 (1932).

[4] A. Seyewetz and P. Sisley, "Antioxidants and Antioxygens," *Bulletin* de la Société Chimique de France, Vol. 32, p. 672 (1922).

[5] See, for example, W. Traube and F. Kuhbier, "On the Autoxidation of Complex Ferric Compounds of Polyhydroxy Alcohols," *Berichte* der Deutschen Chemischen Gesellschaft, Vol. 65, p. 190 (1932).

[6] H. Kauffmann, "Reaction Chains in Oxidation Processes, *Berichte* der Deutschen Chemischen Gesellschaft, Vol. 64, p. 179 (1932).

SYMPOSIUM ON STEEL CASTINGS

HELD AT A JOINT MEETING OF THE
AMERICAN FOUNDRYMEN'S ASSOCIATION
AND THE
AMERICAN SOCIETY FOR TESTING MATERIALS
JUNE 21, 1932

PREFACE

The American Foundrymen's Association and the American Society for Testing Materials have outlined programs for the purpose of providing the engineering profession with authoritative data and information concerning the properties of metal castings. A Symposium on Steel Castings is being presented this year at the annual meeting of the A.S.T.M. under the direct supervision of an Advisory Committee, consisting of the following members:

Wm. M. Barr, Consulting Chemist, Union Pacific Railroad Co.
George Batty, Research Director, The Atlantic Steel Castings Co.
R. A. Bull, Director, Electrical Steel Founders' Research Group.
J. A. Capp, Engineer, Testing Laboratory, General Electric Co.
Fred Grotts, Metallurgical Engineer, Continental Roll and Steel Foundry Co.
R. E. Kennedy, Technical Secretary, American Foundrymen's Assn.
J. H. Locke, Vice-President, General Steel Castings Corp.
Steel Founders' Society of America.
Jerome Strauss, Chief Research Engineer, Vanadium Corporation of America.
C. L. Warwick, Secretary-Treasurer, American Society for Testing Materials.
G. B. Waterhouse, Professor of Metallurgy, Massachusetts Institute of Technology.
W. C. Hamilton, *Chairman*, Research Director, American Steel Foundries.

This Advisory Committee was responsible for the selection of papers and authors and delegated to certain of its members living in the Chicago district, the task of reviewing the papers before their final editing. The members so delegated are: R. A. Bull, R. E. Kennedy and Fred Grotts.

The chairman desires to express now his appreciation to the Advisory Committee, and especially to the three members who have aided him in reviewing the papers, for their hearty cooperation. Also, much credit is due the authors of papers who have devoted their time to this undertaking.

In many cases material included in the papers has been accumulated from various sources and it is not feasible to give mention to the individuals or companies who have cooperated.

The papers included in this Symposium cover subject matter which it is hoped will be of particular interest to the users of steel castings. The titles present a general idea of the contents of each paper. Much of the material will be of most value as a reference, but in each paper there are facts brought out which are of particular interest, and each author has been requested to give a summary of his paper when it is presented for discussion. Manifestly, it is impossible to cover all phases of the steel-casting industry in a program of this nature; and it, therefore, seems appropriate to present, in an introductory way, a general survey of the steel-casting industry.

W. C. HAMILTON,
Chairman, Advisory Committee on Symposium.

GENERAL SURVEY OF THE STEEL CASTINGS INDUSTRY

By W. C. Hamilton[1]

It may be surprising to some persons that a chronicle of the steel-castings industry in the United States covers a period no greater than about 65 years. Probably the beginning of the industry in this country was in 1867 at the plant of the William Butcher Steel Works, later absorbed by the Midvale Steel Co. The early castings produced at this plant were made into crossing frogs; and there has continued to exist a close relationship between railway engineering and the steel casting industry, now grown to proportions, which, if utilized to full extent, would produce a material in a single year worth more than 200 million dollars.

In the beginning, dry sand molds were used exclusively for the production of steel castings, it being a requirement that they be baked in ovens in order to remove all moisture. The production of this type of steel castings centered largely at Chester, Pa. Probably about 1887, the first successful use of undried or green sand molds was demonstrated on a large scale. In the St. Louis district, the development of the green sand molding practice proceeded especially rapidly, and shops were designed and equipped for the quantity production of railroad specialties.

In these specialty shops, mechanical problems were studied and various improvements resulted in greater economy and a betterment of the product. Hand-rammers gave way to pneumatic tools, which, together with a hammer used in the cleaning room, were developed along the lines of the pneumatic riveter, previously employed for building erection. Many companies were organized which began to devise various types of machines for ramming molds. The jarring machine was found to be especially suited to produce a hard-rammed mold desirable for steel.

These jarring machines were later equipped with auxiliary devices for stripping the patterns and rolling over the molds. Other kinds of equipment to eliminate manual labor for ramming were developed. Squeezing machines for small molds were built in large numbers. At a later date, sand-slingers were introduced into the steel foundry. With these mechanical methods of molding, the problem of service became the vital one. Systems for conveying materials and molds and for shaking out the molds were installed. Similar improvements of a mechanical nature were made in the cleaning rooms where blasting and tumbling equipment was devised.

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[1] Research Director, American Steel Foundries, East Chicago, Ind.

Much study was directed towards the proper preparation of the sand mixtures, and this resulted in many improvements in mechanical mixers, including the well-known pan type of mill. Since 1920, there have been established routine tests to maintain uniformity of sand conditions.

It is, of course, generally known that the original medium for making steel was the crucible pot furnace, but by the time the steel casting industry was established in the United States, the converter and the open-hearth furnace had been developed and were satisfactory units. The open-hearth proved to be an especially suitable furnace for steel castings. Oil became very popular as a fuel, and quite recent developments have provided controls whereby the operations of an open-hearth furnace are well regulated. These changes have led to a better quality of steel and to reduced costs of operation.

In this country, converters have been lined with refractories of an acid nature only; but from the beginning, open-hearth furnaces, with either the acid or basic linings, have been used in the steel-casting industry. The acid linings were at first preferred by the plants in the Chester district where the dry sand castings predominated. The majority of these castings were machined, and in the early days the steel made in acid furnaces was known to be freer of gases. However, with the development of new deoxidizing alloys, basic open-hearth steel has been produced to compare very favorably with the acid steel. The choice today between an acid or a basic open-hearth furnace depends largely upon the location of the plant in respect to the available supplies of purchased scrap.

The electric arc furnace was introduced into the steel-casting industry in this country in 1909 when approximately 343 tons were produced. The output of converter steel for castings, at that time, was approximately 38,000 tons, crucible steel approximately 14,000 tons, and open-hearth steel about 673,000 tons.

The progress made during the past 20 years in electric steel melting in the foundry and elsewhere is a matter of fairly common knowledge among industrialists. Naturally, the increase in the number of electric furnaces for making steel castings has been accompanied by a decrease in the number of converters utilized for the same purpose. Today, the converter, like the crucible pot furnace, may be said to have reached a stage of little commercial importance. Operations of the converter are handicapped by a large loss of metal through the oxidation that takes place in the cupola and to an even greater extent in the converter. In contrast, the electric furnace melts metal with relatively small oxidation losses. This fact somewhat balances the high initital cost of the electric arc furnace and its high cost of operation. A gradual reduction of cost for electric power in many localities has resulted in giving the arc furnace its present economic position. Because of the relatively small capacity of the average electric furnace, it is peculiarly adapted to making a great variety of compositions; and the fact that the temperatures obtainable are limited only by the refractories gives it a decided advantage in the production of castings having thin sections.

The element that greatly influenced the tendency to install arc furnaces was the development in this country of a great many, relatively small, industrial enterprises, which created a steadily increasing and substantial demand for small and medium-size steel castings. They are required in a great many instances in small tonnages, and are best adapted for numerous applications when made from alloy steel. This gave the steel casting industry a great stimulus in the production of special metals, and much progress has been made in the production of alloy steels. The result is that today the proportion of cast alloy steels made in America probably amounts to 20 per cent of the total.

The arc furnace has been employed in the United States for steel casting production with both basic and acid linings, preference generally being for the acid-lined unit, due very largely to its greater simplicity of operation. For certain grades of alloy steels, the basic furnace is preferred, as with it there are less melting losses of the alloys used.

The latest development in the adaptation of electric furnaces for the steel casting industry is the high-frequency induction unit, which has acquired a position of importance for the production of high alloy steels for castings. It is especially suitable for producing alloys having extremely low carbon contents.

In the different types of furnaces enumerated above, the manufacturer of steel castings has available to him melting units ranging in capacity from approximately 100 lb. to 50 tons each. The large capacity furnaces are of the open-hearth type and are a recent development for the production of specialties. The customary size of open-hearth furnaces for steel foundry use is approximately 25 tons. Most of the electric arc furnaces, and the majority of the converters which they displaced, are of three tons rated capacity. Individual furnaces readily take a heat charge varying from a few hundred pounds to five tons in weight. The high-frequency induction furnaces used in the steel foundry range from 500 lb. to slightly over one ton in rated capacity.

A quarter-century ago, steel castings were regarded as a general product, differing chiefly in size and shape. Individual foundries regularly made many varieties of castings, ranging from very small to very large in weight, in cross-section, and in overall dimensions. This idea still exists in the minds of a few foundrymen, who point with pride to their ability to make steel castings regardless of their nature. This false pride has undoubtedly been largely accountable for many of the criticisms which have formerly been directed toward steel castings.

There is a great variety in the products made regularly in steel foundries. These range in thickness from approximately $\frac{1}{4}$ in. to as much as 4 ft.; and run in weight from a few ounces to huge sizes, requiring the simultaneous tapping of several open-hearth furnaces in order to provide sufficient metal. Probably the largest steel casting ever produced was made in an American foundry during the last year. The weight of the finished casting was 460,000 lb. Within the extremes of member-thickness and weight mentioned, there is an infinite variety in overall dimensions. Engine bed castings are successfully produced, having lengths of 65 ft.; and members of intricate design serve to complicate manufacture.

We are now in an age of specialization, which has extended to the steel-casting industry; and it is recognized by most producers that there is a decided limit to the different types of castings which can be produced satisfactorily in one foundry. For example, it would not seem consistent, either from a production or from a selling standpoint, to manufacture Ford and Lincoln cars in the same plant. The adaptation of melting units and many other kinds of equipment for varying classes of steel castings has occasioned a degree of specialization in the steel-casting industry that is not appreciated by many consumers of these products. The most striking illustration is seen in the railroad field. In the old days, failures of castings were common. However, much attention was given to couplers, side frames, and bolsters, both from the standpoint of design and of methods of production. As a result, during the last ten years, failures of these castings have been reduced to a negligible amount—even though service requirements have been decidedly increased.

It would be a needlessly tedious task to attempt to outline the vast numbers of important uses to which steel castings are regularly put in large annual tonnages. The extent to which the product has been successfully introduced in total volume is indicated in some degree by the increasing consumption of steel castings during the present century. According to the statistics compiled by the American Iron and Steel Institute, there were less than 216,000 tons of steel castings made in the United States in the year 1900. By 1929, the total output of the industry had mounted to 1,773,000 tons. A few figures to show the development of alloy steel production in the foundry are interesting. Data accumulated by the American Iron and Steel Institute showed less than 33,000 tons of alloy steel castings as having been manufactured in the United States in 1910. By 1929, the output of this material was increased to more than 216,000 tons. At this time, probably 300 plants were engaged in the production of steel castings in the United States, including establishments making steel castings as an auxiliary product for application to their own equipment, and not for merchandising as a separate commodity.

Engineers, generally, are familiar to a considerable extent with the enormous ranges in physical properties obtainable from steel, but many do not realize that the steel foundry is producing metal comparable with the different grades of wrought steel products. A study of heat treatments went hand in hand with the additions of alloys, and the combined effects have resulted in available steel castings having tensile strengths from 50,000 to 200,000 lb. per sq. in. This fact again emphasizes the importance of specialization which has already been discussed.

The authors of papers in this Symposium covering steel castings are presenting information and data which should be useful to both producers and consumers, but especially to the latter.

Steel, as is well known, is a very complex product and there is no other metal or alloy which approaches it in its capacity for modification of properties with slight changes in composition; nor its unique response to heat treatments.

Many of its characteristics are presented in this Symposium, and while remarkable physical properties are being obtained, it is well to emphasize that persistent research will undoubtedly enhance these properties to a degree far above any results known today.

STATISTICAL DATA ON STEEL CASTING PRODUCTION IN THE UNITED STATES

By G. P. Rogers[1]

The statistical information regarding the steel castings industry found in this paper was obtained from several sources, including three organizations that periodically assemble and report statistics on the production of steel castings in America. For several years the U. S. Department of Commerce, through its Bureau of the Census, has issued monthly reports of the output and bookings of steel castings, classified according to miscellaneous and railroad applications. Annually the Department presents summaries, to convey an intelligent, comparative idea of the demand for this product. The Department's statistics embrace only commercial steel castings produced for sale. Companies having foundries exclusively used for supplying their own steel casting requirements do not report to the Department of Commerce. More than half of the data giving total tonnages for bookings and production reported by the Department of Commerce are collected by the Steel Founders' Society of America, and are contributed in total to the Bureau of the Census each month.

For a considerable period the American Iron and Steel Institute has annually distributed reports that include figures on steel castings production, among data showing the outputs of many kinds of steel products. Periodically, the Institute compiles and publishes information as to the capacities of the steel-casting and other industries. The Institute's statistics cover totals only, of production of both commercial steel castings and steel castings made for their own use by producing companies. In these data capacity figures are classified under the following headings: "For Sale," "For Sale and Own Use," and "For Own Use."

The Steel Founders' Society of America has, for several years, annually assembled information for its members and the entire industry, showing capacity, production and other statistics regarding steel castings. So far as the author knows, it is the only source of statistical information giving separate tonnages of steel castings produced for sale as such, and those produced for use by the makers. Naturally the author is more conversant with the statistical information assembled by the Steel Founders' Society of America, the organization with which he is connected, than with data reported from other quarters. However, the author has not restricted himself, for the preparation of this paper, to information regarding what are called commercial steel castings, although naturally they represent much the greater portion of the industry's output. It has been recognized that this effort to give a concise but comprehensive idea of the tonnages produced should attempt to include all steel castings made in the United States.

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[1] Managing Director, Steel Founders' Society of America, Inc., New York City.

TABLE I.—PRODUCTION OF STEEL CASTINGS IN THE UNITED STATES, NET TONS BY PROCESSES, 1898–1930.

	OPEN-HEARTH	ELECTRIC	CONVERTER	CRUCIBLE	MISCELLANEOUS	TOTAL
1898..........	135 057	......	3 964	4 743	4 005	147 769
1899..........	190 096	......	4 412	3 920	4 417	202 845
1900..........	198 790	......	7 243	4 468	5 439	215 939
1901..........	337 817	......	7 576	4 398	5 888	355 678
1902..........	412 024	......	14 054	5 550	6 219	437 847
1903..........	448 390	......	20 271	6 058	7 178	481 897
1904..........	339 174	......	17 977	4 825	7 860	369 836
1905..........	589 725	......	24 755	6 421	7 158	628 059
1906..........	806 278	......	36 513	11 584	12 174	866 550
1907..........	836 108	......	37 266	11 461	14 656	899 491
1908..........	349 190	......	23 026	9 264	6 287	387 766
1909..........	673 165	343	37 872	14 205	9 407	734 991
1910..........	966 953	1 478	65 335	16 388	3 577	1 053 732
1911..........	639 734	2 103	63 953	15 714	2 718	724 222
1912..........	975 350	4 661	77 000	23 016	2 588	1 082 616
1913..........	1 019 442	10 312	90 167	19 680	3 633	1 143 233
1914..........	676 835	9 577	73 788	12 528	3 707	776 435
1915..........	823 572	25 832	103 573	16 527	1 340	970 843
1916..........	1 317 623	48 014	159 926	10 473	338	1 536 375
1917..........	1 358 735	72 700	178 385	4 294	262	1 614 376
1918..........	1 277 730	121 292	180 145	1 490	123	1 580 779
1919..........	854 022	124 891	110 671	1 130	2 888	1 093 609
1920..........	1 104 768	173 820	117 578	1 936	3 625	1 401 727
1921..........	486 578	95 306	43 466	824	703	626 879
1922..........	930 438	173 580	53 461	1 170	....	1 158 649
1923..........	1 290 922	264 273	75 613	2 186	....	1 632 995
1924..........	962 549	231 335	59 849	1 542	....	1 255 276
1925..........	1 027 695	313 078	60 294	2 053	....	1 403 120
1926..........	1 104 327	365 618	48 234	2 286	....	1 520 465
1927..........	923 210	330 186	42 587	1 501	....	1 297 484
1928..........	941 378	390 396	31 864	1 403	....	1 365 041
1929..........	1 268 164	469 324	34 528	989	....	1 773 005
1930..........	877 490	341 803	16 656	773	....	1 236 721

It is apparent from data accumulated, that approximately 83 per cent of all steel castings made in the United States are produced in plants termed commercial foundries, selling the product as steel castings, for application by other manufacturers. The same percentage, roughly speaking, applies in respect to the number of steel foundries, since among the total of about 300 plants that have contributed to the industry's entire output, approximately 240 belong in the commercial group. Of the latter number—in 1929 when the production of steel castings reached its highest point—probably 185 plants made miscellaneous castings in the jobbing trade. It is estimated that, at the present time, there are about 150 jobbing steel foundries operating in this country. It may be stated in this connection that the number of plants particularly equipped for the manufacture of cast-steel specialities (mostly for railroad use) is pro-

Table II.—Production of Steel Castings in the United States, Percentages of Total Outputs by Processes, 1898–1930.

	Open-Hearth	Electric	Converter	Crucible
1898	91.40	.....	2.68	3.21
1899	93.71	.....	2.17	1.93
1900	92.06	.....	3.35	2.07
1901	94.98	.....	2.13	1.24
1902	94.10	.....	3.21	1.27
1903	93.05	.....	4.21	1.26
1904	91.71	.....	4.86	1.30
1905	93.86	.....	3.94	1.02
1906	93.04	.....	4.21	1.34
1907	92.95	.....	4.14	1.27
1908	90.00	0.01	5.94	2.39
1909	90.06	0.05	5.15	1.92
1910	91.76	0.14	6.20	1.56
1911	88.33	0.29	8.83	2.17
1912	90.09	0.43	7.11	2.13
1913	89.17	0.90	7.89	1.72
1914	87.17	1.23	9.50	1.61
1915	84.83	2.66	10.67	1.70
1916	85.76	3.12	10.41	0.68
1917	84.16	4.50	11.05	0.27
1918	80.83	7.67	11.39	0.09
1919	78.09	11.42	10.12	0.10
1920	78.81	12.40	8.38	0.14
1921	77.62	15.20	6.93	0.13
1922	80.30	14.98	4.61	0.10
1923	79.05	16.18	4.63	0.13
1924	76.68	18.43	4.77	0.12
1925	73.24	22.31	4.22	0.15
1926	72.63	24.05	3.17	0.15
1927	71.16	25.45	3.28	0.12
1928	68.96	28.60	2.23	0.10
1929	71.53	26.47	1.95	0.06
1930	70.95	27.64	1.35	0.06

portionately smaller than the outputs of such foundries. Many of these specialized plants that do not make miscellaneous castings have large capacities and are readily capable of supplying the periodically heavy demands characteristic of railroad purchases, as made over a period of years.

STATISTICS COMPILED BY THE AMERICAN IRON AND STEEL INSTITUTE

At the time this paper was written, the American Iron and Steel Institute had not published the production figures for 1931. The quantities of steel castings made, as announced by the Institute, are given in gross tons, although it is the practice of the foundry industry to use the net ton basis of weight. The Institute has compiled information giving, separately, the tonnages of each kind of steel, according to melting process, put into castings, for each year beginning with 1898

TABLE III.—ALLOY STEEL CASTINGS MADE IN THE UNITED STATES, OUTPUTS, 1910–1930.

	NET TONS		NET TONS		NET TONS
1910	32 880	1917	75 632	1924	96 262
1911	63 044	1918	74 463	1925	126 093
1912	115 482	1919	50 817	1926	163 633
1913	99 598	1920	76 555	1927	163 345
1914	78 227	1921	45 086	1928	190 045
1915	109 644	1922	66 196	1929	216 071
1916	63 233	1923	103 286	1930	141 264

Table I shows the quantities of steel castings classified in respect to process, made in the United States from 1898 to 1930, inclusive, according to the information assembled by the American Iron and Steel Institute. Tables I and II, and Fig. 1 were originally published in their present forms (net tons being given) in *Research Group News*,[1] in July, 1931. Table II shows the production of steel castings in the United States for the same 33-year period, by percentage calculated for each of the four melting processes, from the tonnages of plants reporting to the American Iron and Steel Institute. Figure 1 shows graphically the percentages produced by each of the processes for the period of time covering the assemblage of such information by the Institute. This organization has reported the tonnages of alloy steel castings made from 1910 to 1930, inclusive. This information is given in Table III, the quantity units again being converted into net tons. It will be noted that the proportion of alloy-steel castings to total steel castings made in 1930 in the United States was approximately 11.5 per cent.

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[1] Reproduced here by consent of Electric Steel Founders' Research Group.

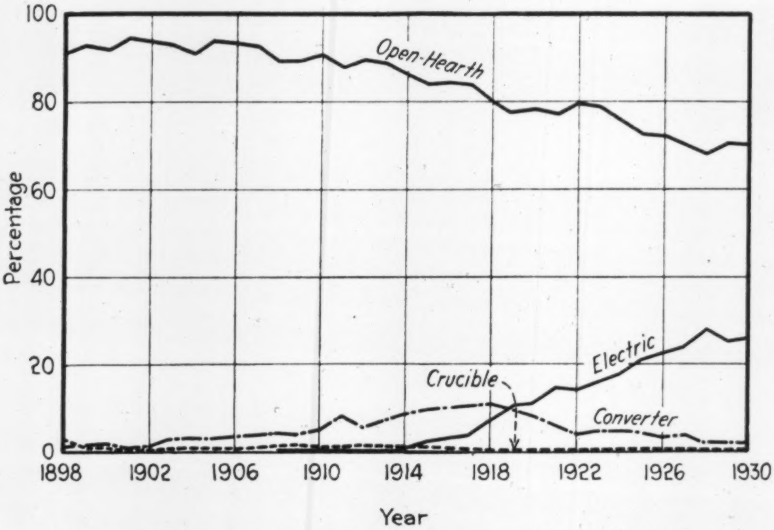

FIG. 1.—Steel-Casting Production in the United States. Percentages by Processes.

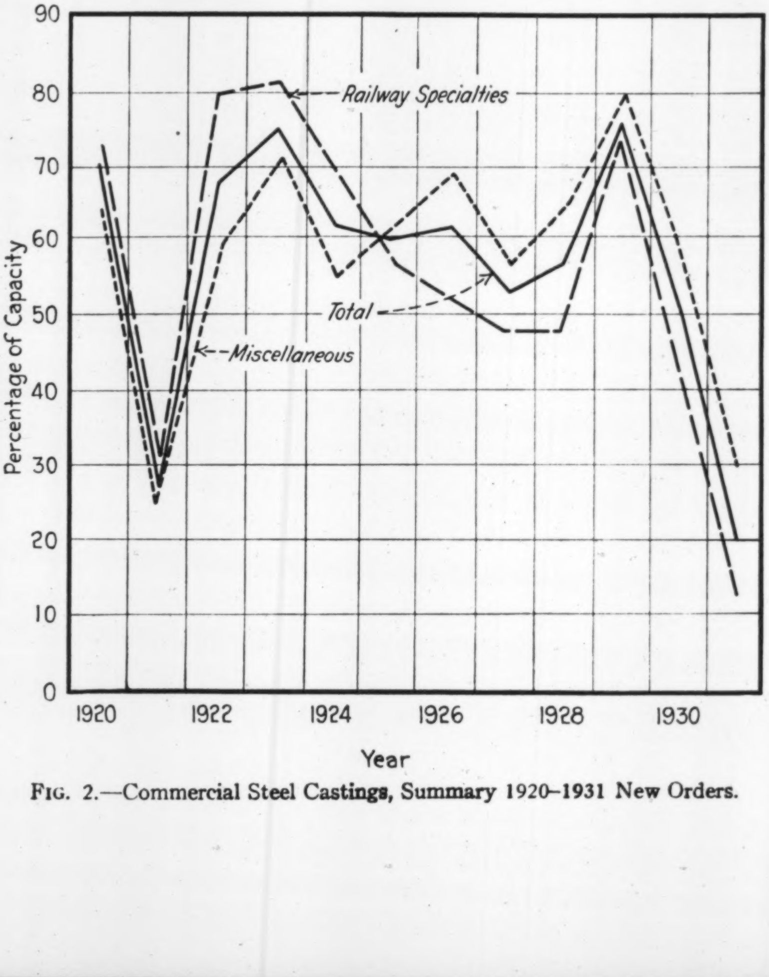

FIG. 2.—Commercial Steel Castings, Summary 1920–1931 New Orders.

STATISTICS COMPILED BY U. S. DEPARTMENT OF COMMERCE

In February, 1932, the U. S. Department of Commerce, through the Bureau of the Census, distributed information resulting from the tabulation of data obtained from those steel-casting concerns that had voluntarily supplied the Government with information on bookings and output. The Bureau announced that its figures came from 132 plants reporting shipments. Accompanying the tabulations a graph was published which is reproduced herein as Fig. 2, showing curves for railroad specialties of cast steel, for miscellaneous steel castings, and for total steel castings. The figures used as a basis for the curves were the percentage of capacity, according to the information available to the Bureau.

Information from other statistics regularly published by the Government regarding steel-casting production is not quoted in this paper because other data herein are believed to give a sufficiently comprehensive idea of the output for the present purpose.

STATISTICS COMPILED BY THE STEEL FOUNDERS' SOCIETY OF AMERICA

The information in this section relates exclusively to the output of commercial foundries making steel castings for sale as such, although complete statistics including production of castings for own use are gathered by the Society. The record year of 1929 recorded the manufacture of 1,370,000 net tons of commercial steel castings produced in approximately 240 plants in the United States. In the following year the output of this material was just under 1,000,000 net tons, representing the product of approximately 220 foundries.

A comparison of production with existing capacity for the last two years for which figures are available at this writing, shows the following:

	PRODUCTION, NET TONS	CAPACITY, NET TONS	PRODUCTION, PER CENT OF CAPACITY
1929	1 370 000	2 015 000	68
1930	1 000 000	1 965 000	51

In the above computations, rated capacity, as reported by the foundries, constitutes the average of the best six consecutive months' shipments since 1921.

Production by Melting Process:

In 1930, about 71 per cent of the commercial steel castings produced were made in open-hearth foundries, 28 per cent of the total

Table IV.—Consumption of Commercial Steel Castings in the United States, Net Tons by Industries for the Year 1929.[a]

Industry	Net Tons
Airplanes	18
Agricultural machinery	9 109
Automotive equipment	11 040
Baling machinery	25
Boiler equipment	2 153
Brass and copper mills	368
Brick machinery	521
Bridge construction	6 083
Buckets, shovels and dredges	21 319
Cement-mill machinery	4 828
Chemical-plant equipment	175
Ceramic machinery	29
Coke-oven equipment	43
Concrete-pipe machinery	79
Construction machinery	417
Conveyors	499
Cranes, hoists and derricks	12 753
Dairy machinery	26
Ditchers	396
Domestic heating furnaces	24
Electrical machinery	10 210
Elevators	1 086
Engines, pumps and compressors	8 764
Explosives	31
Flour-mill machinery	84
Forging equipment	6 569
Foundry equipment	3 248
Gas-producer equipment	235
Gear cutters	1 104
Glass machinery	1 018
Hardware	114
Heat-treating equipment	4 225
Industrial locomotives	130
Industrial trucks	1 308
Irrigation equipment	15
Jacks	388
Laundry machinery	20
Lumber machinery	1 696
Machine tools	9 311
Manholes and gratings	21
Marine and deck equipment	5 120
Mine and quarry machinery and equipment	3 589
Miscellaneous machinery	889
Packing-plant machinery	726
Paper-mill machinery	1 347
Pipe (tube) mills and machinery	1 467
Pneumatic tools	1 481
Power-plant equipment	11
Presses (hydraulic and power)	9 715
Printing presses	793
Pulverizing and crushing machinery	626
Radio equipment	1 236
Refinery and oil-well equipment	11 642
Refractory uses	1 062
Refrigerating machinery	170
Roadmaking machinery	10 038
Rolling mills (including some steel rolls)	50 427
Rolls, alloy steel	8 187
Rolls, carbon steel	1 763
Rubber-tire machinery	2 839
Safes and vaults	98
Shoe machinery	13
Smelting equipment	25
Steam railroads (including electric locomotives)	191 003
Street-lighting equipment	3
Street railways	1 623
Sugar machinery	2 341
Textile machinery	111
Tobacco machinery	6
Tool and die equipment	24
Tractors, trailers, industrial cars	17 678
Transmission machinery	268
U. S. government work	897
Valves and fittings	11 478
Wire-making machinery	22
Wire-rope fittings	35
Woodworking machinery	6
Miscellaneous, all others	24 946
Total consumption	483 183

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[a] Figures obtained as a result of a market survey conducted by the Steel Founders' Society of America, Inc. Reports were received from 134 steel foundries in the United States, but some plants reporting their figures were foundries producing steel castings for their own use only. Tonnages reported by the latter class of foundries are not included in the above tabulation.

representing electric steel castings, and a little over one per cent constituting converter output. Castings of crucible steel accounted for less than 0.1 per cent of the total. These percentages varied only slightly from those for 1929.

A check of the number, size, and type of open-hearth furnaces located in active steel foundries in 1930 showed there were approximately 212 furnaces in the United States having capacities ranging from 3½ tons to 75 tons each. The size most in use is the 25-ton capacity furnace, of which there were 66 reported, representing over 31 per cent of the total number in operation. Next came the 30-ton capacity open-hearth furnace, of which there were 39. Furnaces of 20-ton capacity stood third, with a total of 29. These three sizes comprised considerably more than one-half of the total in operation in the industry.

The data on electric furnaces in the United States were divided between electric-steel foundries supplying the regular, structural trade, and foundries making heat- and corrosion-resistant alloy castings. In the first group, an S.F.S.A. survey showed 248 furnaces, of which 61 were of 1½-ton capacity. Next came the 3-ton size, of which there were 57 reported. There were 25 each of the 6-ton and 2-ton sizes, the 1-ton furnace coming fifth with 22. These five sizes constituted over three-quarters of the total number.

Among the sizes and types of furnaces used for the production of heat- and corrosion-resistant alloy castings, the one-ton electric arc and the 1000-lb. electric induction furnaces stood first, there being seven of each. The 500-lb. arc furnace came next, with a total of six, and the 1000-lb. arc, fourth, with four. These four types represented one-half of the total number of furnaces used in this branch of the foundry industry in the United States during 1930. Nine induction furnaces were reported as being in use by foundries making heat- and corrosion-resistant alloy castings.

The size of converter most in use is the 2-ton, of which there were 22 in the United States in 1930, out of a total of 35 converters in operation.

In the United States there were 19 crucible furnaces in operation in 1930, more than one-half of which were the 6-pot type.

Steel Casting Consumption by Industries:

While there is no known analysis of all steel casting consumption by industries for any one year, Table IV is believed to be fairly representative and indicative of the approximate distribution of the product.

NOTES ON THE DESIGN OF STEEL CASTINGS

By F. A. Lorenz, Jr.[1]

Influence of Old Cast-Iron Designs

Many of the designs produced today in cast steel have altered in no great degree from the essential features of their prototypes of the cast iron era. An examination of wood cuts and photographs of early machines will reveal the persistance with which empirical principles have carried down to our modern designs.

Steel, in its cast form, has suffered because of this inheritance. For generations before its advent engineers had developed their structures with iron as the material for such parts as were to be cast. The first steel casting made in the United States was produced in 1867. Available in its cast form, steel was used as a substitute for cast iron in parts which had failed because of lack of strength and resistance to shock. The engineers assumed that a design which could be cast in iron could be cast in steel with equal facility. There was no information at hand to indicate that modifications should be made in design to facilitate the production of the new material through adaptations to its characteristic behavior in the foundry.

The foundrymen who undertook the casting of steel were not familiar with its behavior, and often mistook the adverse influence of design as being problems of foundry technique. Their efforts were directed toward the production of current designs in steel, and the limited information at their command prevented the realization that modifications in design were necessary. It was a new art, and the fact that its adaptation was paramount, perpetuated the principles of cast-iron design instead of creating and establishing those of steel.

An example of this heritage is the locomotive drive wheel center. Despite the advances which have been made in other units of the locomotive, a comparison of the drivers of a modern engine with those of "The General," of Andrew's Raid fame, will reveal an identity in their design. Only within the last year have designs been developed which take into consideration the difficulties of producing the traditional cast-iron design in cast steel, and provide for ease in production while taking advantage of the characteristics of steel for improvement in service.

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[1] **General Manager,** Industrial Division, American Steel Foundries, Chicago, Ill.

COOPERATION BETWEEN DESIGNER AND FOUNDER

Steel castings lend themselves with great facility to the varied necessities of design. The wide range of their application in industry indicates the dependence placed upon them. This range grows greater as the designer and the foundryman reach a better understanding of their related problems and as the objectives of the one are conditioned to meet the facilities and technique of the other.

It is not necessary that the foundryman be qualified as a designer, nor that the engineer be thoroughly versed in foundry practice. The common ground of their interest is the most economical production of a casting which embodies the desired characteristics of utility and appearance. Economic considerations justify whole-hearted cooperation in order that the penalties of high production costs and impaired soundness may be avoided.

There is a tendency among foundrymen to devote their energies to the production of designs as submitted, without bringing to the attention of the engineers the features which impose high production costs. This failure to indicate the offending features of design leaves the designer ignorant of economies which could be effected. Occasionally, when the designer is prompted by economic reasons to resort to a fabricated or forged substitute, he finds that radical changes in construction are involved, to accommodate the limitations of the manufacturing process selected. It is quite possible, that, had the foundryman presented his requirements for economical production, suitable alterations in the design would have been made. It is also possible that the designer would have been able to retain desirable features which he was forced to sacrifice in the substitute.

To the designing engineer belongs the initiative in bringing about cooperation between himself and the foundryman. Originating in his mind, the design is developed and ultimately presented to the foundryman for his quotation of price. Too frequently the design is developed with no great consideration of changes which might reduce the cost of production or of modifications which would improve the ability of the casting to withstand the stresses imposed in service. These are important considerations, and much benefit may be gained if the broad fundamentals of steel founding are understood by the engineer, or if he will avail himself of the information which a steel foundryman can give as the design is in process of development.

It may not be an exaggeration to state that it is as essential in developing a design to understand the characteristics and behavior of steel in the mold as to know its characteristics and behavior under working conditions. The stresses set up in cooling, the starvation of obscure sections, the influence of one section upon another, and the numerous factors entering into the production of steel castings bear strongly upon the cost and the ability of the casting to meet the conditions of service to which it is put.

CONTRACTION AND CRYSTALLIZATION PHENOMENA

The temperature at which steel for castings is tapped from the furnace is usually in excess of 2800° F., the nature of the castings to be poured regulating the requirements of temperature. Castings of heavy section may be poured with metal of lower temperature than can those of light section, requiring very fluid metal.

Although the loss of heat begins immediately upon the tapping of the metal from the furnace, the most drastic drop occurs at the instant of contact of the metal with the surfaces of the mold cavity. The chilling effect of this contact causes the instantaneous formation of a skin of solidified metal. The casting for a short period consists of a shell, the interior of which is filled with fluid metal. Figure 1 shows a section of a simple block which was bled by breaking an opening 15 seconds after pouring was complete. This illustrates the rapidity with which the shell of solidified metal is formed.

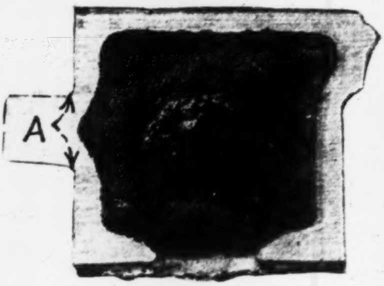

FIG. 1.—Casting Shell, Formed by Bleeding 15 Seconds After Pouring Was Complete.

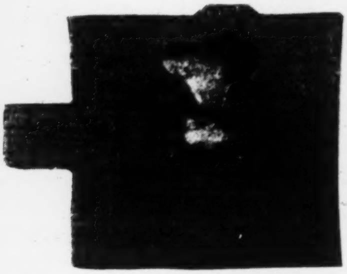

FIG. 2.—Section Showing Shrinkage Cavity.

Formation of Crystals:

Steel, as it solidifies, forms crystals, and the shell created by contact with the mold surfaces is of crystalline structure increasing in thickness as the temperature of the interior, due to loss of heat through the shell, reaches a point where additional crystals are formed upon its inner surface.

This formation of crystals also involves a contraction as the change from the liquid to the solid state takes place. The action of the formation of the crystals is progressive and takes place from all directions toward the center. That area, being the last to solidify, continues to supply the demands for material until it is exhausted. In the absence of a source from which it, in turn, may draw needed material, the demand goes unsatisfied and a shrinkage cavity results. Figure 2 shows a section through a block which was allowed to solidify with no provision for supplying the material needed to compensate for the shrinkage. Figure 3 illustrates the same type of block upon which was placed an adequate riser or head as a reservoir from which the block was able to satisfy its requirements for material.

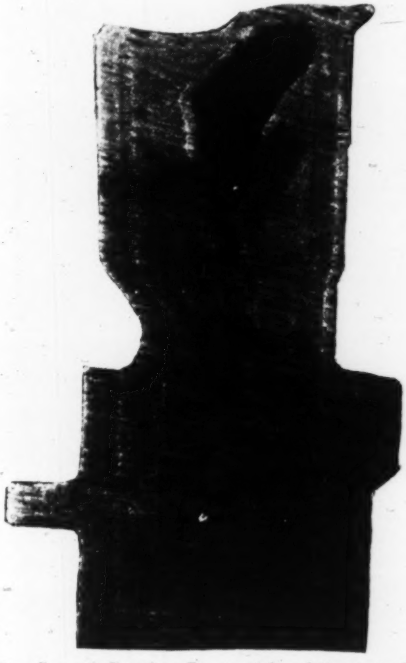

FIG. 3.—Sound Casting Insured by Adequate Riser.

Feeding of Sections:

This necessity for adequate feeding should always receive the serious attention of the engineer. If it is not possible to incorporate uniformity of section in the design, the location of heavy sections should be such that they may be readily supplied with material from conveniently located risers, or be fed through an adjacent section of sufficient bulk. In general, sections located in the lower parts of the mold draw material from those sections immediately above them.

These are, in turn, fed from the surplus provided in the superimposed risers. Invaluable assistance can be rendered in the production of sound castings if, in the designing, the sections are arranged to facilitate proper feeding.

Figure 4 indicates the manner in which the locations of sections, in relation to others, influence the ultimate soundness of a casting. The casting is represented by sections A_1–A_2, B–B_1, C_1–C_2, and the risers by A and C. In cooling, A_2 is fed by A_1, which, in turn, receives material from riser A. Sections B and B_1 due to their lightness, cool almost instantaneously and require little feeding. Such material as is needed is supplied by the adjacent sections. The location of heavy section C_2, below the lighter section C_1, effectively shuts off its supply of material. The provision of excess metal in riser C is ineffective, because C_1 is lighter than C_2, and solidifies before the latter. The result is the shrinkage cavity at D.

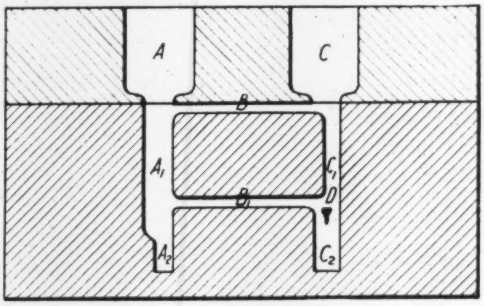

FIG. 4.—Showing Relation of Sections of Various Thickness.

Effect of Heat Transmission:

A comparison of the rapid, almost instantaneous solidification of the thin sections, with the slower, progressive freezing of the heavy sections, indicates that the capacity of the surrounding sand for carrying away heat is limited. This is also shown by the boss on the bled casting in Fig. 1, which has progressed much further in its solidification during the same time interval, than has the block proper. The surface area of the boss is greater, in proportion to its mass, than that of the body of the block. Its proportion of radiating surfaces to the volume of heat in its mass permitted rapid cooling.

Figure 1 shows, in addition to what has been mentioned, the effect produced by connecting members. The sand which formed the sharp corner at the junction A, of the boss with the block, was called upon to transmit heat from the surface of the boss, as well as from the surface of the block. The double duty imposed upon this area was greater than its capacity, and the lag in transmission is evidenced by the thinness of the skin at the juncture. Though the time interval was but fifteen seconds, the effect of the retardation is quite evident.

Provisions for Heat Transmission:

The same tendency exists at the junctures of all sections and is apt to be evidenced in the form of a shrink unless proper precautions are taken to reduce the abruptness of the union. The simple expedient of providing suitable radii at such points serves to increase the area of the radiating surfaces, and provides for an approximately uniform cooling rate throughout. This method is shown in Fig. 5. The introduction of properly proportioned fillets, by eliminating sharp corner of sand, provides surfaces capable of more rapid heat transmission than could otherwise be effected.

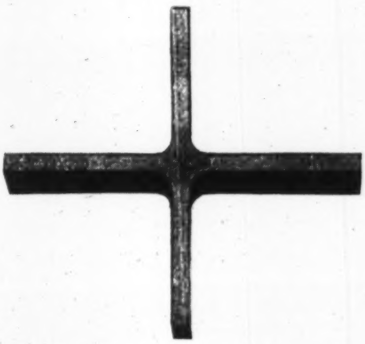

FIG. 5.—Showing Provisions for Heat Transmission by Use of Fillets.

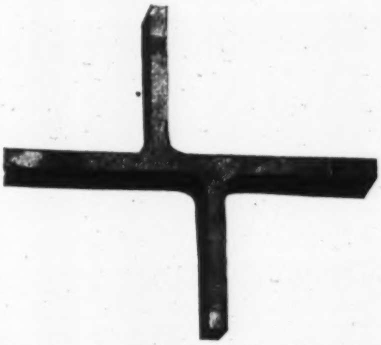

FIG. 6.—Casting Employing Staggered Section.

There are occasions when such a junction, because of the size of the sections, creates a mass of such size as to require the use of risers to insure solidity. Such a condition, and incidental difficulties tending to cause shrinkage cracks, may often be avoided by staggering the sections, as shown in Fig. 6. Cross-ribs, the functions of which are largely those of reinforcement, particularly lend themselves to this form of relief.

Figure 7 illustrates an expedient adopted to reduce the concentration of heat at the junction of the cross-ribbing and the body of the casting. Normally, risers would be required at these points to insure solidity. Instead, relief cores, *A*, were placed to provide the openings shown, thereby reducing the mass at the point of heat concentration, and providing a relatively uniform rate of cooling. There are numerous instances in which such troublesome masses can be reduced by variations of this procedure, with no sacrifice of strength,

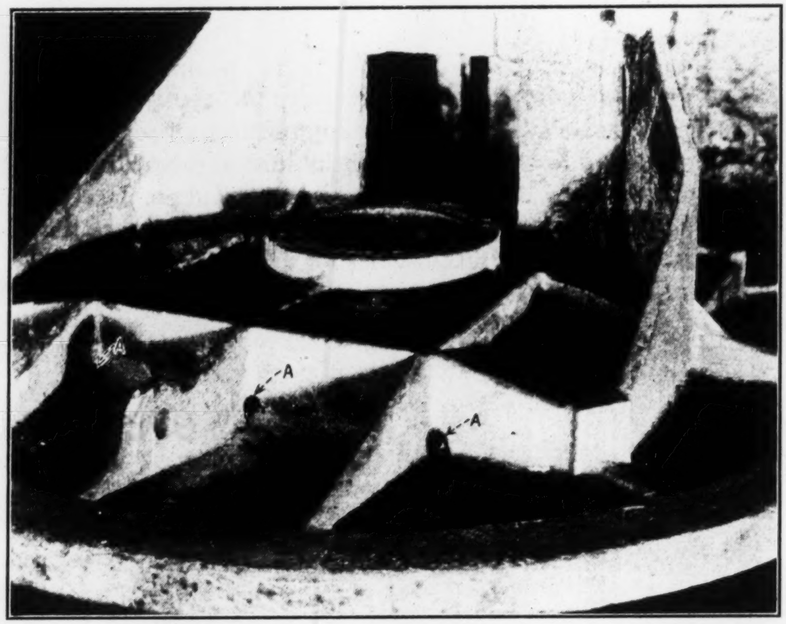

FIG. 7.—Use of Holes to Reduce the Concentration of Heat at the Junction of the Cross-Ribbing and the Body of the Casting.

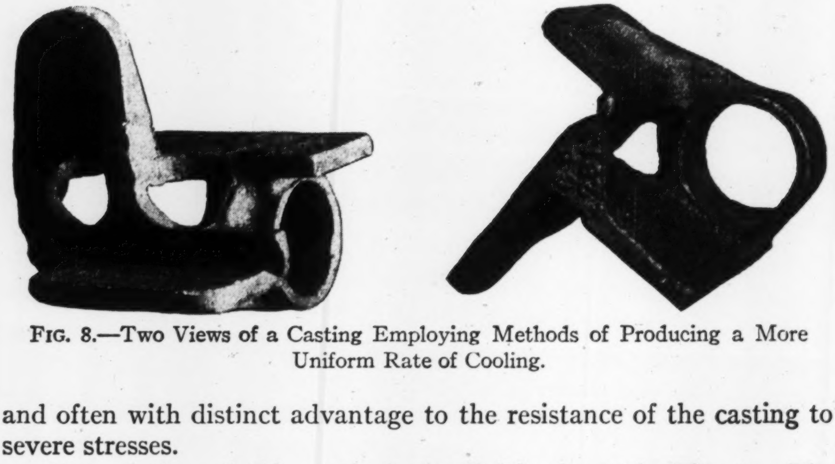

FIG. 8.—Two Views of a Casting Employing Methods of Producing a More Uniform Rate of Cooling.

and often with distinct advantage to the resistance of the casting to severe stresses.

A variation of this method of relief is shown in Fig. 8. The casting was molded in the vertical position, with the ring up. The two views indicate the ways in which the members were relieved by openings, while sharp corners were eliminated. The result was a component of a machine which combined lightness of weight and great resistance to service stresses. Serious strains were not induced in the solidification of the steel because the design accommodated itself to contraction phenomena.

Deep Pockets:

Deep pockets which have sharp interior corners, or which are produced by bodies of sand of insufficient area to properly conduct the heat of the surrounding metal, are to be avoided. Such pockets produce the difficulties of sharp corners and also present the disadvantages of difficult removal of sand. If pockets cannot be avoided, as many and as large openings as possible should be made, to permit heat transfer and to facilitate the removal of sand. A difficulty similar to that of deep pockets is shown in Fig. 9. Here, a core of small area was surrounded by a large mass of metal. Its inability to conduct heat rapidly maintained the adjacent metal in a fluid state longer than the metal in the riser. An excessive amount of feed metal had to be provided to correct the shrink which occurred.

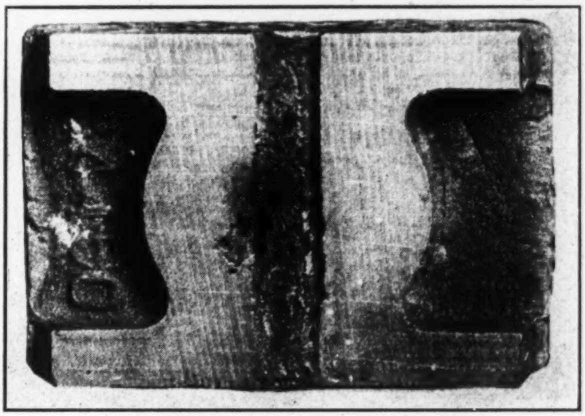

FIG. 9.—Shrinkage Caused by a Core of Small Area Being Surrounded by a Large Mass of Metal.

The junctions of bosses or trunnions with other sections of the casting are frequent sources of difficulty. Bosses are often of greater cross-section than the members to which they are joined. This inequality gives rise to a serious concentration of heat at the junction. Provisions should be made in such instances for as near an approach to equalization of sections as possible. This may be accomplished by the use of adequate fillets, and by coring out the boss so that its section is comparable to that of the member to which it is joined. This equalization of section not only assists in the produc-

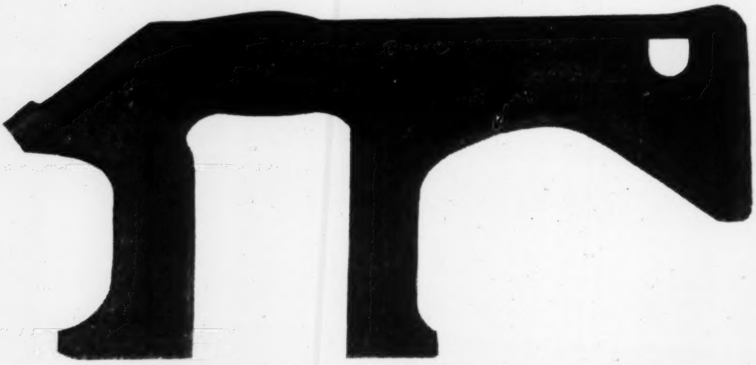

FIG. 10.—Sweeping Curves Used to Avoid Radical Changes in Direction.

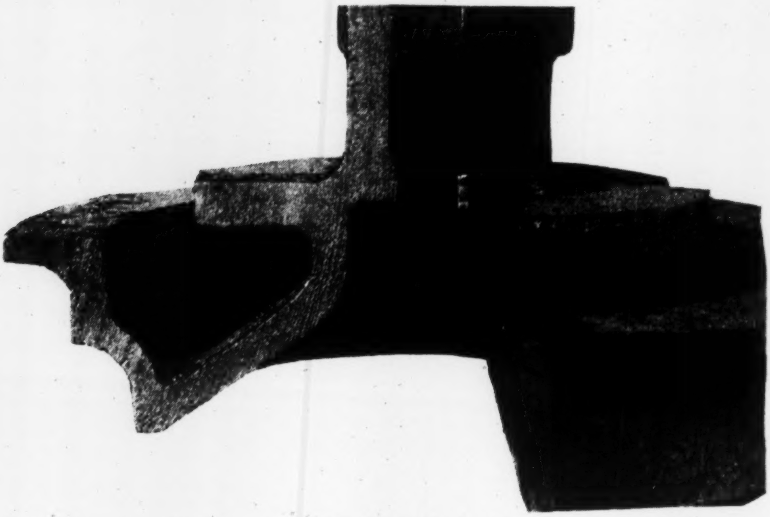

FIG. 11.—Cut-Away Section of a Cylinder-Head Casting Showing Properly Proportioned Sections.

tion of sound castings, but does much to avoid the concentration of stresses imposed in service, wherever changes in section are abrupt.

Section Uniformity:

Abrupt changes in cross-section are invariably to be avoided. The expenditure of time to devise ways of avoiding them is amply repaid in the improved ability of the casting to meet the conditions of the service to which it is put. The joining of a light section to a heavy section, even though adequate fillets are provided, imposes severe stresses at the point of union, both in the cooling of the casting and under load in service. Such a condition may often be relieved by a proportional thickening and thinning of the two sections to bring them at least to practical equality. This produces a far stronger unit because of the material reduction in stress concentration. It is often found that by an equalization of sections throughout the design, weight can be saved and strength can be greatly increased.

FIG. 12.—An Example of Inequality of Section.

The results obtained by Kommers and Moore[1] in rotating-beam tests upon bars 0.40 in. in diameter show the drastic effect of the concentration of stresses in abrupt changes in cross-section. In each bar the section was reduced to 0.275 in. in diameter at its center. In the bar in which this diameter was reached by a 9.85-in. radius, the endurance limit was 49,000 lb. per sq. in. By using a $\frac{1}{4}$-in. radius, this value was reduced 8 per cent. With a square shoulder, it was reduced 51 per cent, and with a V-notch, 60 per cent.

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[1] *Bulletin No. 124*, University of Illinois Engineering Experiment Station, Urbana, Ill. (1921).

The computation of fiber stress at points of unmodified changes of section is difficult if not impossible, because of inability to determine the influence the change exerts in concentrating load stresses. That the influence is great and that such conditions should zealously be avoided whenever possible, is obvious. Figure 10 shows an excellent example of the use of sweeping curves to avoid radical changes in direction. The flange at *A* swells gradually to accommodate the change from $\frac{1}{2}$ in. to the $\frac{7}{8}$-in. metal of the column head, which, in the broad curves of *B* and *C*, forms the union with the upper flange of the extension. Such features are not only desirable from the standpoint of load distribution, but lend themselves admirably to the satisfactory production of the casting.

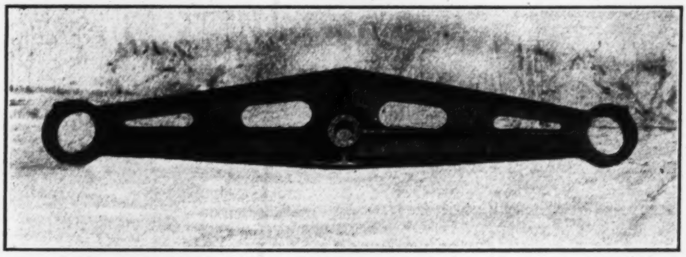

FIG. 13.—Illustrates the Preferred Uniformity of Section.

Figure 11, showing a cut-away section of a cylinder head casting, is an example of desirable uniformity of section and gradual direction changes of various members. Not only is the casting designed to produce an equalized distribution of load, but a simplification of foundry problems is accomplished. Figure 12 presents an example of gross inequalities of section. Extreme difficulty is experienced in the foundry in preventing serious cracks in the light, cross-shaped spokes. These cracks are caused by the wide difference in the cooling rate of the thick hub and rim, and of the thin spokes. The suggested modification of this design involves an increase in the size of the spoke section, with a proportionate reduction in section of both the rim and hub.

The casting shown in Fig. 13 is an example of preferred uniformity of section. In it, each member is designed in such a manner that full advantage is taken of the inherent strength of the material, with no feature tending to impose conditions which would impair the casting.

Linear Shrinkage:

The linear shrinkage of steel as it cools from the liquid state involves an actual movement of the casting through the sand. In the case of a perfectly flat piece with no projections such as flanges, bosses, or brackets, normal unimpeded contraction will take place.

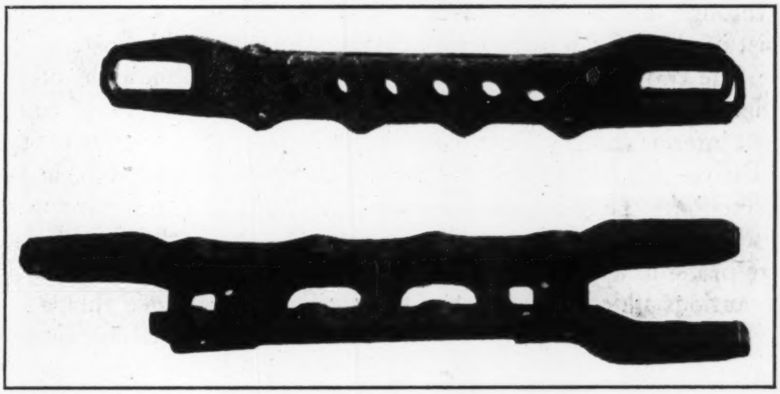

FIG. 14.—Two Views of the Original Design of a Casting the Molding of Which Involved the Use of Complicated Interior Cores.

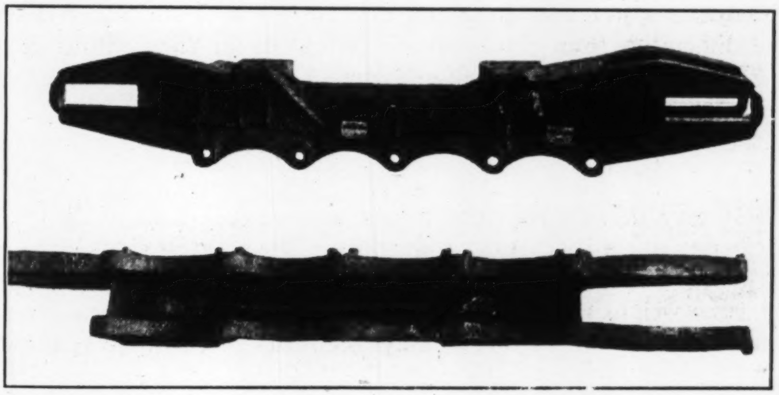

FIG. 15.—Two Views of a Casting Which Is a Re-designing of That Shown in Fig. 14.

The presence of such details reduces the measurable contraction because such details prevent unrestricted movement. It is not always possible to predetermine the exact extent of this influence on contraction when the pattern is being made, and at times this causes a delay in producing a casting dimensionally correct.

Shrinkage or contraction concerns the designer largely because of its influence on the cost of castings. The foundryman must take into consideration the expense entailed by the precautionary steps in producing a casting free from cracks and cavities caused by shrinkage or contraction. Many safeguards of practice are applied successfully for this purpose in addition to normal production methods, but they necessitate extra manufacturing expense. The designer, either through his general knowledge of the behavior of the metal in cooling, or through information obtainable from the foundryman, can greatly assist in obtaining a satisfactory casting at a reasonable cost.

The two views of the casting shown in Fig. 14, show the original design of the piece, the molding of which involved the use of complicated interior cores. These cores necessitated not only elaborate and expensive core box equipment but required special attention in their production. They required a special sand mixture and extreme care in setting the cores in position in order to avoid the cracks which were prone to appear as the metal contracted over the cores. These precautions added to the cost of production and retarded the progress of the castings through the shop. The re-designed casting, shown in two views in Fig. 15, eliminated the use of interior cores, and permitted the pattern to leave its own core when withdrawn from the sand. Cores were required to produce the brackets and ribs on the exterior, but the equipment was simple and the cores were produced at a much lower cost than the interior cores of the other design. The difficulties from cracks were eliminated, for the contour of the new design lent itself to self-adjustment in cooling, and in general proved a decided improvement over the old construction.

FACTORS INFLUENCING COST

It may be said that the weight of a casting does not in direct proportion affect its cost of production. The greatest single influence in this respect is the degree of intricacy of design. Two castings of the same weight may be at the extremes of high and low production costs. The simplicity of one may assure its rapid progress through the manufacturing operations, while the other, due to complicated design, may require special effort at every stage of its production. A premium in selling price must be exacted for this additional cost.

Where equalization is not possible, the junctions of the unequal members should be as gradual as possible and be accomplished by fillets, tapers or curves. These devices avoid the detrimental concentration of stresses which are not only pernicious in their effect upon the strength of the casting in service, but increase the difficulties of production. The expenditure of time in modifying a design to eliminate or reduce to a minimum the number of cores required will usually be repaid in an appreciable reduction in the cost of the casting.

The staggering of sections as shown in Fig. 6 and the relief of heavy junctions as shown in Figs. 7 and 8, are helpful devices in securing uniformity in cooling rate and in avoiding the use of excessive feed metal. The observance of these precautions will do much to reduce the cost of the casting and insure its integrity.

Pattern Equipment:

Pattern equipment plays an important part in determining the cost of castings. Whether or not the foundryman is to be intrusted with the manufacture of the pattern, his suggestions as to its construction should be given much consideration. His judgment as to the expense which may properly be incurred is based upon an appreciation of the length of time a pattern may be expected to produce castings of dimensional accuracy.

Frequently quotations for pattern equipment made by commercial pattern manufacturers are based upon the production of the equipment, and not upon its greatest utility in the production of castings. This is apt to prove costly when the bids for castings from it are received, and it is possible that the engineer's efforts to produce a satisfactory steel casting design may be defeated. There are many variations in pattern construction of which the pattern maker may take advantage. Some of these, while lowering pattern costs, impose unnecessary expense in producing the casting. Sections may be attached as loose pieces which would more properly be made by the use of a core. A core may be used where the results would be far more satisfactory, if more extensive pattern work permitted the section to form its own core. The construction of pattern equipment should always be given serious consideration and be planned as the result of experience and keen observation. It is not enough that a casting can be produced from a pattern. It must be constructed with proper consideration of its maximum utility.

APPLICATION OF METALLURGICAL KNOWLEDGE ACQUIRED

Metallurgically, the modern steel foundry has made significant progress. Research laboratories have met and anticipated demands by developing new alloys of outstanding merit. Unfortunately, inadequate contact between the designing engineer and the foundryman has prevented application of information gained by all the advances which have been made. Designs are daily presented to the foundryman in which the development of sections was obviously based upon strength factors of low-carbon rolled material. In many of these designs advantage could be taken of the properties of special steels produced in the foundry by means of which weight could be reduced and serviceability could be improved. In many well-established cast alloy steels there may be obtained augmented values for yield point, ultimate strength and ductility. Certain grades of metal, also well-established, provide marked resistance to corrosion and abrasion. Data on these properties are indispensable to the builders of equipment for the most effective revision of existing designs and for the most intelligent development of new ones. Only through the close cooperation of the engineer and the foundryman can these designing functions be properly performed.

DISCUSSION

MR. C. W. BRIGGS[1] (*presented in written form*).—Mr. Lorenz believes that if the designing engineer will avail himself of the information which a steel foundryman can give, much benefit may be gained. Just how much information can a steel foundryman give?

In the first place, take the steel itself. How much do we know about the actual laws of mass action? Sauerwald has definitely pointed out various discrepancies along this line, in his studies on steel and slag equilibriums. The steel that goes into the castings is not controlled as to physical and chemical correctness. The fluidity of such steel varies according to these conditions. Is it not true that fluidity is a very important factor?

What is definitely known about the formation of hot cracks? At what temperature range do they occur? Korber and Schitzkowski claim around 1300° C. (2370° F.), although others headed by Osann claim as low as 600° C. (1110° F.). Definite information should be obtained before we tell the designer how to eliminate these cracks, since we are not agreed as to the temperature when they are formed. What are the differences as to the nature of the internal hot crack and the hot crack that definitely opens at the surface? Various opinions, but nothing very definite, have been advanced regarding this. Considerable has been said regarding the importance of shrinkage in cast steel. Some persons invariably forget about the plastic state of the metal, and the great temperature gradients found in castings, such as when a contracting portion of the casting actually elongates another portion which is in a very plastic state.

Then again, how important is the expansion due to the pearlitic formation? We are inclined to think that it is noteworthy in the consideration of the formation of the so-called low-temperature hot crack.

We have heard much about the strength of steels and their ability or inability to resist certain stress at temperatures near the solidification range, but I would point out that there are no definite figures available. This is indeed unfortunate when you wish to study the effect of stresses set up by contraction on the solidifying casting.

I should also like to call attention to the various opinions on the thickness of initial solidifying envelopes. Some declare that these envelopes are rather thick and of very great importance. Others, such as Singer, claim that they are very weak and are continually being cracked and filled up with molten metal from the interior; and that there is very little difference in the temperature gradient between the inner and outer portion of the casting. These factors are all very important in connection with the design of castings.

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[1] Physical Metallurgist, U. S. Naval Research Laboratory, Washington, D. C.

There are other problems, such as those related to internal chills, differential cooling in varying cross-sections, the relation of thickness to initial cracking, etc., that I have not mentioned, which, no doubt, are engaging the attention of foundrymen.

MR. H. H. LESTER[1] *(by letter)*.—The author has presented some very interesting facts regarding the influence of design on casting quality. The writer has been engaged since 1922 in the inspection of steel castings and has studied many of the effects pointed out. Mr. Lorenz is justified in his plea for greater cooperation between the designing engineer and the foundry metallurgist.

At Watertown Arsenal defects most frequently encountered traceable to design have been:

1. Entrapped gases and dirt, usually in the cope, due to pockets or to thin sections that fill from adjacent heavy sections, and in which there is no definite flow from the gate toward a riser.
2. Incomplete feeding in parts isolated from risers or from members that could function as reservoirs of metal.
3. Cracks caused by mold or core.

In connection with feeding, the writer wishes to emphasize the points made by the author. Metal flow is not that of a free liquid. It is due in part to tensions set up in the moving metal. In this flow of a viscous material through constantly constricting channels, separations occur which are really pipes. The fine pipes, often microscopic in dimensions, tend to enlarge through the accumulation of gases.

Most of the modifications in design that have been made in remanufacture of castings after rejection at Watertown have had to do directly or indirectly with the question of feeding.

With regard to cracks caused by mold or core, it may be remarked that perhaps greater emphasis is given such cracks over those caused by the union of unequal sections, sharp fillets, etc., because cracks of the latter type have been considered more carefully in the design of ordnance castings, and have been largely but not completely eliminated.

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[1] Research Physicist, Watertown Arsenal, Watertown, Mass.

Among cracks caused by projecting members one prolific source of difficulty has been the test coupon. This is the more apt to cause trouble because the designer does not ordinarily provide a location for it, or for two or three of them. They are, in many cases, difficult to locate in positions where they will not cause serious tensions in the cooling and shrinking metal.

MR. W. M. BARR.[1]—The question was raised as to how much the foundryman can tell the designer. I think that is largely a matter of cooperation. It has not been many years ago when it might have been difficult to get very much information from the foundryman to help the designer, but I think that has very materially changed. The development in the foundries of their research departments has brought technical men into the foundries as executives who, today, can tell the designer a great deal. It is extremely important that cooperation be developed along this line. The designer should take up matters of this kind with the technical representative of the foundry. In that way I think that a great deal of improvement can be made, to the advantage of the consumer. The railroad companies use some large castings, including those rather difficult to make. I know that railroad executives do not want their men to be arbitrary in making designs without regard to the method of production and the advice of the foundrymen. Very often, by friendly conference, difficulties can very readily be avoided.

MR. R. H. CANFIELD.[2]—To one who is something of a newcomer to the field of casting metallurgy, the outstanding characteristics of these remarks about design is their rather indefinite character. I think it is to that that can be traced the difficulty people are encountering. To cite an example: In fabricating structural steel, any detailer knows that a rivet hole can only go $\frac{3}{8}$ in. from the edge of the plate, and a lot of other little definite facts like that, but so far as I know, there are no rules which have ever been formulated of anything like that definite character for casting design. Anything can be fabricated as a general proposition, but what I refer to is, what is the normal satisfactory thing?

Now, as a definite suggestion to those in the casting industry, this may perhaps be a little absurd, but it does not seem so to me. Everybody else makes specifications for your castings and your steels; why don't you make some specifications for design?

MR. JOHN HOWE HALL.[3]—There is very little in print today about the proper design of parts to be cast. One man asked me three or four years ago if I would not undertake, in collaboration with him or somebody else, to write a treatise that both the producer and consumer need, on proper design. Possibly it should be the other way around, and describe the typical "boners" in design of steel casting. If Mr. Lorenz, or Mr. Fry, who asked me to do that, or some of these other gentlemen who have had long experience in the design of steel castings, would write a small treatise or handbook outlining the principles of the design of steel castings, it would be of the greatest value to both buyers and sellers of castings.

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[1] Assistant to Executive Vice-President, Union Pacific Railroad Co., Omaha, Nebr.

[2] Superintendent, Division of Physical Metallurgy, U.S. Naval Research Laboratory, Washington, D. C.

[3] Technical Assistant to the President, Taylor-Wharton Iron and Steel Co., High Bridge, N. J.

MR. R. A. BULL.[1]—Referring to the hope that foundrymen will cooperate in formulating recommended practices for design, it seems to me to be a perfectly logical thing to look forward to. We foundrymen argue against being limited too closely on chemical composition and on physical properties. We point out that differences in thickness of members and improper connection of members essentially introduce difficulties. We speak our piece when it comes to contact with a particular customer, and try to develop the essential features we believe will give a desirable product. But it seems to me that we might go further than that, probably best through the medium of the Steel Division of the American Foundrymen's Association, and finally develop some recommended practices for design which would meet the needs referred to. I think it is a perfectly logical thing to develop, and it seems to me that consumers, as a class, can consistently look to the producers of steel castings, to try to work out something of that sort.

[For other discussion relating to the design of steel castings, see discussions of the papers by R. A. Bull and Jerome Strauss, pages 106 and 231.—ED.]

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[1] Director, Electric Steel Founders' Research Group, Chicago, Ill.

PURCHASE REQUIREMENTS FOR STEEL CASTINGS, WITH NOTES ON PHYSICAL PROPERTIES IN TEST BARS AND IN COMMERCIAL CASTINGS

By R. A. Bull[1]

A comparative analysis of the most significant requirements in authenticated specifications for steel castings calls for a preliminary explanation of an interesting, unprecedented situation. It is well known that, after the World War, interest was vigorously aroused in alloy steels for many wrought products. The foundry quickly felt the effect of, and demonstrated for itself, this spirit of inquiry. Since it became alloy-conscious, the steel-casting industry has been going through a period of vigorous investigation, involving the gradual accumulation of data regarding those properties in foundry alloy steels, which, after each of the several heat treatments that may be applied, can be said correctly to be typical, providing the basis for reasonable, minimum requirements in commercial specifications.

Delay in Specifications for Special Steels

It was natural for the production of special steels for castings to reach a state of much industrial importance considerably in advance of agreements by producers and consumers regarding those chemical and physical characteristics that may consistently be required by purchasers. During the last ten years, the proportion of the foundries in America making one or more kinds of special steels has steadily increased. Experience in such manufacture, gained by some producers at a comparatively early date, resulted in conclusions regarded by them as being reliable in respect to properties that can confidently be expected when such material is properly manufactured. The lesser experience of other producers makes them cautious in offering guarantees, and they have felt justified in delaying the formulation of specifications for the class of material they now manufacture.

It is generally recognized that a commercial specification is intended to cover only the properties ascertained after the material is made, not according to extraordinary measures for obtaining high quality, but according to customary practices usually admitted to be proper and feasible, considered in relation to the prices normally asked for the commodity. Except when a specification happens to have a peculiar significance clearly indicated by its title or its phraseology, it is not regarded as an index to the result of production by means of technique or equipment of extraordinary character, for the class of material specified.

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[1] Director, Electric Steel Founders' Research Group, Chicago, Ill.

Although a committee of the American Society for Testing Materials has endeavored for several years to assemble information covering typical properties of each of a variety of well-known foundry alloy steels, no conclusion regarding rejection limits to apply to any of them has yet been reached, with the exception of a single specification tentatively adopted in 1930,[1] for castings of austenitic manganese steel, often termed Hadfield's manganese steel. Despite the delayed adoption by the Society of specifications for several familiar kinds of foundry alloy steels, several large consumers have established purchase requirements for such products, which, apparently, these buyers believe are applied satisfactorily. Some of these private specifications are abstracted in a section of this paper.

Attending the development of alloy steels, there have been many important facts learned regarding heat treatment, as applied not only to that product of the steel foundry which has a special or unusual chemical composition, but to cast material of the common or carbon grade. Enlightening facts, ascertained when experimenting with differing heat treatments given to alloy steels, have prompted some founders to determine whether unusual properties in carbon steel might be obtained by heat treatment combinations not ordinarily given such a product. As a result, some manufacturers have been induced to give carbon-steel castings draw and liquid-quenching treatments that have developed physical properties of great interest, not only when compared with those in full-annealed or in simply normalized carbon steel, but with the properties in certain alloy steels.

For the reasons indicated, the situation, for a decade at least, has been an experimental one in the steel-casting industry as a whole. A vast amount of highly useful information has been assembled gradually. Experienced producers who have shown no tendency to follow tradition blindly, have reached conclusions prompting them to give the purchaser guarantees that cannot be found in specifications approved by any technical society. This applies not only to alloy or special steels but to carbon or common steel, and necessarily involves heat treatment as well as chemical composition. In this connection, the author prefers to explain that his use of the term heat treatment implies any method of applying and withdrawing heat, whether the procedure is simple or complex and whether or not the heat application is followed or preceded by another one of any kind. Thus, normalizing and full annealing (the latter term meaning furnace cooling) are included. This is in agreement with accepted modern terminology, which prescribes that the single word anneal may be used to describe either a normalizing or a full-annealing operation without making a distinction as to cooling inside or outside the oven in still air.

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[1] Tentative Specifications for Austenitic Manganese-Steel Castings (A.S.T.M. Designation: A 128-30 T), *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part I, p. 969 (1930); also 1931 Book of A.S.T.M. Tentative Standards, p. 80.

DESIGN FACTORS INFLUENCING TEST SPECIMEN RESULTS

Before presenting a summary of specifications for steel castings adopted by national organizations, or formulated by large consumers for their own use, it seems advisable to explain certain factors that are not fully understood by consumers regarding the manner in which the member of a casting generally influences its physical properties, as ascertained by laboratory tests.

Much work has been done in the effort to determine the influence of thickness on such properties as yield point, ultimate strength, elongation, and reduction of area in the tension testing of cast metals. Mass is a highly important factor in any metal product, influencing its resistance to stresses. The effect of mass is significant because it largely controls the speed with which the metal cools. The differing results caused by rapid cooling and by slow cooling are noticeable in the case of every metal. Investigations have been conducted in a great many foundries fully demonstrating this fact in connection with steel, malleable iron, gray iron (simple and alloy), and the nonferrous metals.

Occasionally consumers have shown a disposition to specify the physical properties listed in commercial specifications in efforts to prescribe tests from much heavier sections of metal than are customarily used for the preparation of laboratory specimens. These purchasers have wanted to determine the properties in the individual members of castings under immediate consideration. Such a desire may be frankly admitted by foundrymen to be perfectly reasonable, in the absence of information, such as the casting producers have accumulated, demonstrating, for example, that the properties in a cast-steel member 4 in. thick differ from the properties in a member of the same casting, 1 in. thick.

There is no satisfactory way now known to the metal maker by which he may fully counteract the influence of slow cooling in its effect on the structure and performance of steel or any other metal.

The skilled foundryman, to some extent, can compensate for differences of thickness, as by influencing the cooling rate through such expedients as chills (used more often externally than internally) to accelerate solidification. But the extent to which such devices may be employed is limited, and the contrasting degrees of cooling, in the case of radically differing thicknesses of metal, may be observed in the testing of specimens, vital portions of which are taken from the central sections of members of variable thicknesses.

Some years ago, several metallurgists, members of a committee of the American Society for Testing Materials, were delegated to investigate the effects of size and location of test coupons. The committee's report, presented before the Society in 1927, contained the following statements:[1]

> 1. No general rule can be laid down for the location and dimensions of test coupons. They must be located so as not to "bleed" the casting and yet must be fed so as to be sound. They must be large enough in cross-section to cast solidly and not be porous or dirty. These are matters for determination in individual cases and must necessarily be determined by manufacturing conditions.
>
> 2. Tests reviewed by the committee show that when the flame-cutting is done with reasonable skill, the partial severance of the test-coupon by flame-cutting before annealing of the casting does not affect the properties obtained upon specimens taken from the coupon. The tests show no difference in results from completely attached and partially severed coupons on the same casting.
>
> 3. Tests reviewed by the committee show no definite or consistent relation between test results from specimens machined from coupons and results upon specimens machined from the body of the castings to which the coupons were attached. These tests covered a wide variety of sizes (cross-sections) of castings and varying dimensions of coupons in proportion to the cross-section of castings where attached. With castings produced and annealed under good average commercial conditions, the tests show:
>
> (*a*) A tendency toward lower tensile properties, especially elongation and contraction, on specimens machined from the body of thick castings as compared with results upon specimens machined from attached coupons of the moderate thickness customarily used.
>
> (*b*) That many other factors influence results beside proportions and locations of test coupons to body of casting, hence no rule more specific than the statement of tendency in (*a*) may safely be stated.

In all probability there are more differences in physical properties found in steel, when comparing very light with very heavy sections from the same heats, than are found in testing some other metals. It is natural that this should be so because of the high temperature necessary for the pouring of steel, due to its relatively low carbon content. The factor last named is the one responsible for the tendency of the metal to chill quickly. Material like gray iron, which has a much larger proportion of carbon than has steel, is characterized, purely as a result of its relatively high carbon content, by a much higher degree of fluidity at a given temperature. The relatively low degree of fluidity of steel necessitates discharging it from the furnace at a high temperature. When steel that has been introduced into a sand mold fills a cavity designed for a very thick member, the resulting slowness with which the section cools develops a granular structure that is not formed in the light member that freezes quickly. If the section of the heavier member is thick enough, there will occur the phenomenon of segregation, developed solely by reason of the extended period during which the material remains in a fluid state.

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[1] Report of Sub-Subcommittee, of Committee A-1, on Size and Location of Test Coupons on Steel Castings, *Proceedings*, Am. Soc. Testing Mats., Vol. 27, Part I, p. 114 (1927).

There is another factor that very often influences the physical properties of steel. This relates to the several phenomena of contraction or shrinkage and the opportunity given a selected portion of any member to have its needs for contraction fully satisfied by a reservoir of metal. This may be in the form of a sink-head or riser that will subsequently be removed, or in the form of a superimposed casting member having a thickness sufficient to permit it to function as a riser. Unless the thick portion of the steel casting has been poured in such a position as to permit feeding action by gravity to occur as contraction takes place, there will be a lack of such density in the heavy section as is essential for providing a test specimen having all the desired physical properties.

The contraction of steel is considerably greater than that of many other metals, roughly averaging $\frac{1}{4}$ in. per ft., when a casting of simple design, having no significant cross members, is used as a basis for shrinkage measurement. Steel in the foundry is poured at temperatures adapted for the work in hand. The metal intended for very thin castings may be tapped from the furnace at a temperature of approximately 3000° F. (1650° C.), and is apt to contract in the order of $\frac{5}{16}$ in. per ft. when poured into a mold of extremely simple shape, corresponding somewhat to a plank, joist, or I-beam. In the steel foundry specializing in the manufacture of castings having very heavy sections, the heats intended exclusively for such work are tapped at considerably lower temperatures than the one mentioned, with a resulting diminution in the degree of contraction during solidification and cooling.

The extent to which feeding is required for the purpose of providing complete homogeneity of structure in the heart of every member is regulated in some degree by the pouring temperature, and also, by the chemical composition of the steel. Certain elements have more influence on shrinkage than do others. But while there are variables in casting temperature and in chemical composition, the carbon percentage in any heat of steel is such as to make it contract, as the metal cools, to a degree that requires considerable compensating material, in the absence of which the physical properties in the center of the member (where, of course, solidification takes place last) will be injuriously influenced.

Following many experiments with various metals, foundrymen and consumers of cast products who have had an opportunity to familiarize themselves with the conditions indicated have had no other reasonable recourse than to agree among themselves that a specimen for laboratory testing to determine acceptability of the metal should be made in such a way as to demonstrate the physical behavior of the material, when poured under commercial conditions approaching the ideal. In steel, such conditions call for a reasonably quick solidification, so as to develop no unduly coarse, crystalline structures, to afford no opportunity for appreciable segregation of chemical constituents, and to safeguard against the lack of density that is so seriously influenced by the opportunity for feeding.

The better suitability of the separately made test specimen for determining the degree of satisfactoriness of the metal in castings, as compared with the selection of a specimen from a member in a commercial casting, has been endorsed by many accredited metallurgists who have given much thought to this matter. Prominent among these men is Doctor Rosenhain, until recently Superintendant of the Metallurgy Department of the National Physical Laboratory of Great Britain. In March, 1932, in an address delivered at a meeting of the (British) Institute of Metals, this distinguished scientist went into detail for the purpose of explaining the practical reasons for the preferred use of a separately made test specimen for judging the acceptability of metal in castings.[1]

Some years ago the author published the results of tests conducted when comparing the physical properties in each of a number of members of commercial castings, made under conditions that might, perhaps, be supposed to produce satisfactory results in all portions of the castings selected for experimentation.[2] The accompanying illustrations and tabulations will serve to explain what was ascertained, without the necessity for much elaboration.

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[1] Walter Rosenhain, "Testing of Castings," *Foundry Trade Journal* (London), March 10, 1932, p. 154.

[2] *Research Group News*, January 1928, p. 164, and April, 1928, p. 175.

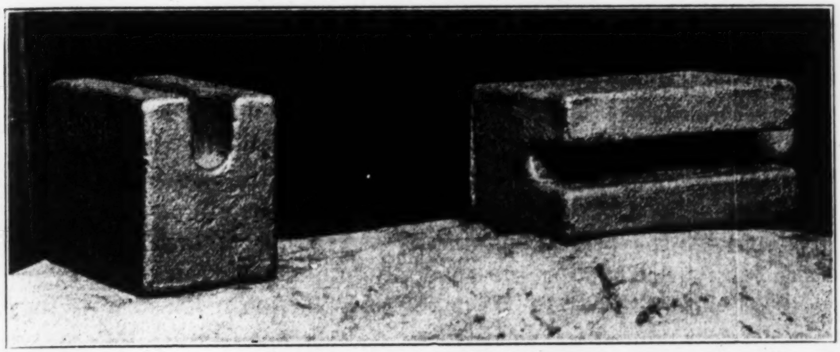

FIG. 1.—Views of Customary Type of Steel Foundry Tension Test Block.

FIG. 2.—Test Coupon on Member ⅜ in. Thick, of Casting Poured with Coupon Down.

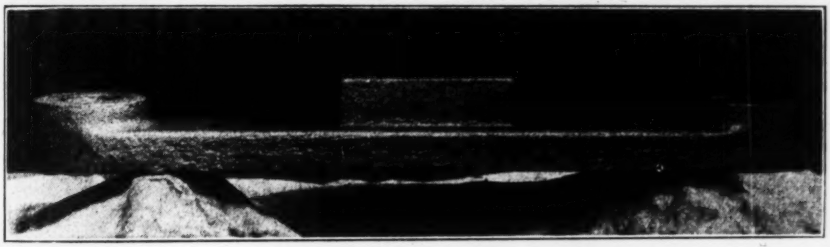

FIG. 3.—Test Coupon on Member 1¼ in. Thick, of Casting Poured with Coupon Down.

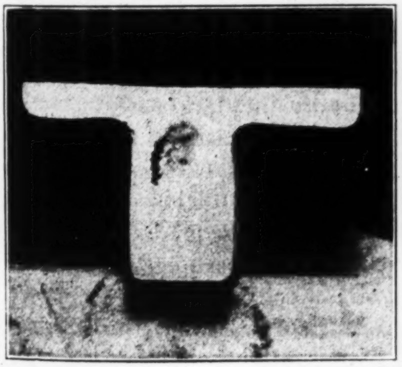

FIG. 4.—Section of Coupon on Casting Shown in Fig. 2.

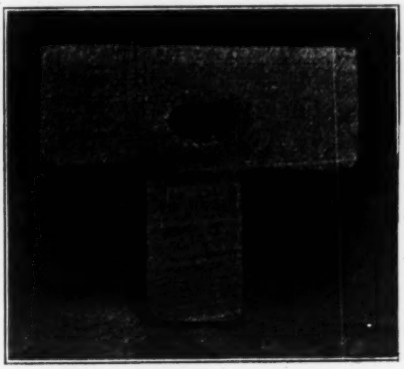

FIG. 5—Section from Coupon on Casting Shown in Fig. 3.

Figure 1 shows a type of tension test block as made frequently in the steel foundry. The ribs are cast under the heavy feeding plate, which serves as a reservoir to supply the two coupons with adequate metal to compensate for contraction. Ordinarily the feeding plate is not less than 2 in. thick. The number and length of the ribs are regulated by the desired number of test specimens. The coupons made for tension testing are generally about 1 in. thick and $1\frac{1}{4}$ in. deep. Figure 2 shows a test coupon in a position reversed from that cast. When poured the single rib or coupon was beneath the central portion of a relatively thin commercial steel casting. Figure 4 shows the result of sectionalizing the casting shown in Fig. 2, to ascertain the condition in the coupon. The lack of density gradually acquired the status of a well-defined cavity, shown by the dark portion in the upper left-hand part of the rib, which here is illustrated in the position as cast, under the thin plate. Figure 3 shows a casting similar to that in Fig. 2, the difference being in thickness. This casting was poured with a single test coupon lying under the plate, the latter having a thickness sufficient to feed the rib subsequently used for tension testing. The coupon was sound, contraction having been compensated for by the surplus metal in the overlying plate member. But because of the thickness of the plate and the absence of a riser

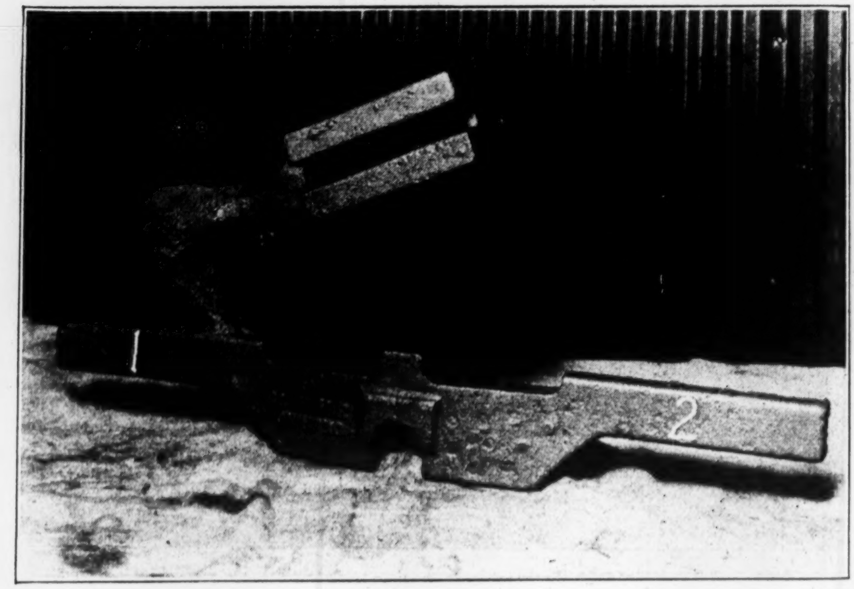

FIG. 6.—Method of Casting Specimens Reported in Table I.

over it at the location of the rib, a large shrinkage cavity was formed in the plate member, as shown in Fig. 5. This demonstrates the manner in which a satisfactory test coupon may be obtained, occasionally, when attached to a commercial casting, but at the expense of the latter. A coupon may result directly in serious unsoundness of the casting feeding it. This is a very important possibility that should be kept in mind. Figure 6 shows a frequently used method of making a commercial steel casting, the design of which does not lend itself satisfactorily to the attachment of a test coupon. In this case the test block, having two ribs, is shown attached to the casting proper, by means of a runner. For experimental purposes, two locations in the commercial casting were selected for preparing tension test specimens. The results of the tests are given in Table I. Figure 7 shows another commercial steel casting used to determine the difference in tensile properties found in taking various portions of the casting for test. Four locations that were selected are indicated in the figure. This shows, by the location of the gate and the riser, that the casting was lying on its side when photographed (considered in relation to the position as poured). Table II shows the tension-test results obtained from this experiment. The casting in Fig. 7 was approximately 11 in. square and $\frac{7}{8}$ in. thick. To it was attached, by means of a runner, a standard test block having two coupons, the results of testing one of which are given in Table II, for comparison.

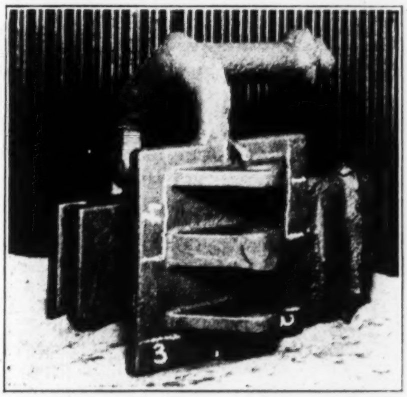

FIG. 7.—Method of Casting Specimens Reported in Table II.

These examples demonstrate the variable conditions found in the hearts of castings of different thicknesses, poured under the necessarily differing conditions that influence feeding action and speed of solidification. It is apparent that the degree of resistance to certain kinds of stress, which characterize interior portions of the steel casting, frequently cannot be gaged satisfactorily from the performance of the coupon made under conditions as nearly ideal as they can be maintained. This condition prevails also in the case of castings of other metals, because laws of Nature operate to produce these results.

That the condition of mass is highly influential in the case of the steel forging has been demonstrated by tests reported to the American Society for Steel Treating by W. J. Merten.[1] This investigator found in various locations, in carbon-steel forgings $8\frac{1}{2}$ in. thick, tensile strength values ranging from 71,375 to 91,125 lb. per sq. in., and values for reduction of area ranging from 5.5 to 39.1 per cent. These forgings were tested in the condition as regularly made, and were submitted by the producers as ready for machining and application.

TABLE I.—RESULTS OF TESTS MADE ON CASTING SHOWN IN FIG. 6.

	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation, in 2 in., per cent	Reduction of Area, per cent
Test block coupon	69 650	39 240	26.5	47.5
Section 1	60 410	37 540	8.0	17.0
Section 2	53 920	36 940	7.5	14.5

TABLE II.—RESULTS OF TESTS MADE ON CASTING SHOWN IN FIG. 7.

	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
Test block coupon	73 390	39 040	28.0	46.0
Section 1	72 500	36 500	29.0	44.6
Section 2	72 900	37 940	23.0	35.3
Section 3	73 040	38 040	28.0	44.6
Section 4	70 300	38 940	18.5	26.8

Those who have not been familiar with the performance of steel castings in service and who have not, perchance, had the opportunity of considering the effects of mass in respect to shrinkage and other phenomena, might, without further reference to this important subject, experience a feeling of insecurity regarding the behavior of those steel castings which have several important members of appreciable thickness, required for applications involving severe stresses. It is here that the factor of safety comes into play. It must be taken into consideration by the engineer, in the case of every material he uses. It is perfectly proper to call it the factor of experience, because it has become the basis for engineering calculations only as a result of observing the performance of materials when and after they are stressed in service.

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[1] W. J. Merten, "High Temperature Treatments of Castings and Forgings as Evidenced by Core Drill Tests from Heavy Sections," *Transactions*, Am. Soc. Steel Treating, Vol. XIII, No. 1, p. 1, January, 1928.

CHEMICAL LIMITATIONS FOR CARBON STEEL

The subject of chemical requirements for steel-casting specifications needs elucidation, because of the unfamiliarity of some consumers with all the functions of the various elements in the chemical composition of carbon or common steel. Certain specifications adopted in the past by national organizations, and a few specifications formulated within recent years by consumers, have erroneously imposed restrictions on the percentages of silicon and manganese. These elements have important deoxidizing influences on the molten metal. In making steel for castings it becomes essential to degasify the metal as thoroughly as possible, to prevent gas cavities in the castings. These cavities may take the form of porosity or pin-holes, or blow-holes. It is distinctly helpful, in the efforts to prevent such defects, to introduce liberal amounts of silicon and manganese in the form of alloys containing these elements.

In steel-mill practice it is not the custom to put into the metal as large a total amount of silicon and manganese combined, when making carbon or common steel, as it is the case in steel-foundry practice. The reason for this lies in the fact that gas cavities in an ingot are necessarily compressed by the mechanical working of the red-hot steel, to the extent that any cavities completely change their shape and become streaks or seams, if welding itself does not actually take place. Foundry practice, therefore, differs essentially from mill practice, due to the treatment the mill product must receive after the metal fills the ingot mold. Obviously, a cavity of any kind in a casting remains there permanently, unless filled up by some welding process applied after complete cooling has followed solidification.

The author is prompted to cite as a reasonable procedure for consumers, the restrictions in A.S.T.M. Specifications A 95 – 29,[1] the physical and chemical requirements of which are listed elsewhere in this paper.[1] These restrictions impose minimum, not maximum, limits for both silicon and manganese, for the major purpose of assuring proper deoxidation as a safeguard against gas cavities. It is hoped that the specifications mentioned, the last of four developed by the Society for carbon-steel castings, and which, therefore, represent the latest foundry practice, will be used as an example for the preparation of future specifications, and for the possible revision of those containing restrictions against the interests of the consumer.

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[1] Standard Specifications for Carbon-Steel Castings for Valves, Flanges and Fittings for High-Temperature Service (A.S.T.M. Designation: A 95 – 29), 1930 Book of A.S.T.M. Standards, Part I, p. 264.

The metal in the ladle costs more when relatively large amounts of silicon or manganese or both are introduced than when restrictions are followed, calling for comparatively small percentages of these elements. However, the progressive steel-casting manufacturer realizes that the manufacture of the metal constitutes but one of many important factors in the completed production of quality castings, and he prefers always to provide his product with those properties which will make it serviceable to the greatest possible extent, within the practicable limits of cost. Accordingly, the steel founder who has followed the results in all feasible methods to maintain homogeneity, and who has watched the behavior in the laboratory and in the field of cast-steel parts subjected to serious stresses, realizes that an advantage in serviceability is very apt to accrue to the cast product of carbon steel when liberal percentages of silicon and manganese are contained. The steel-casting producer has viewed with satisfaction the dissipation of the former erroneous idea held by some consumers of steel castings, that a manganese content higher than 0.75 per cent was apt to result in brittleness. This opinion was maintained by some purchasers during the early days of the World War. But the effects of manganese in steel as high as 1.75 per cent, widely observed by a great many users during the last five years, have brought a merited appreciation of the beneficial effects of this element. To some extent, too, relatively high silicon content has been recognized as helpful in the same general, two-fold way; that is, for deoxidation and for affecting physical properties.

Those steel founders who have been taken into consultation when specifications for steel castings have been in process of development, have emphasized the very important factor of relationship, when considering the influence of any element in the chemical composition. A high proportion of carbon, silicon, or manganese, to a large extent, is helpful or harmful, according to the proportions of the other elements present. It is fundamentally wrong to evaluate them on any other basis. It thus becomes a perfectly logical procedure to specify physical properties, maximum limits of phosphorus and sulfur, and minimum limits for silicon and manganese; and to allow the producer to follow his own judgment regarding the other constituents in the material intended for steel castings of the carbon or common grade of metal. To avoid being misunderstood, the author would state that he does not classify medium-manganese steel (which frequently contains from 1.25 to 1.50 per cent of manganese) in the category of carbon steel. In the author's opinion, this metal should be graded as a simple alloy steel.

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[1] See p. 93.

Mention has been made of maximum percentages of phosphorus and sulfur that should be specified. There is no tendency to disagree on the limit of 0.05 per cent for phosphorus in steel castings. Unless and until the Joint Committee on Investigation of the Effect of Phosphorus and Sulfur in Steel should ascertain that a higher limit than 0.05 per cent of phosphorus may safely be prescribed for the product of the steel foundry, debate on adherence to this traditional restriction, to safeguard against cold-shortness, would be futile, and inadvisable on technical grounds. But a different condition obtains in respect to sulfur content. The joint committee officially announced several years ago, after a great many tests, that it could find no relationship between serviceability and a sulfur content in steel as high as 0.09 per cent. Quite properly, this conclusion influenced many who were clothed with specification responsibilities. Two of the three specifications for carbon-steel castings adopted by the A.S.T.M., call for a maximum sulfur limit of 0.06 per cent, a restriction entirely agreeable to steel founders as a class. One specification still calls for a maximum sulfur content of 0.05 per cent. The author believes that this, at times, unwarrantably imposes a commercial handicap on the producer, which is transferred to the consumer; and that it will not be long before the maximum sulfur limit for all ordinary classes of steel products, intended for structural purposes, will be established at 0.06 per cent.

IMPORTANT ELEMENTS IN OPTIONAL SHOP PRACTICES

It seems inadvisable to conclude the discussion of the major subject without mention of the many details of shop practice that collectively are of vital importance in the production of sound and thoroughly satisfactory steel castings, considered separately from the physical and chemical characteristics in the metal used for the part. Naturally, many operations required for the manufacture of a steel casting are not subject to control by any procedure described in a specification intended to have application to a general product. Inexperienced inspectors do not always realize this fact. Some purchasing agents who have not had an opportunity to familiarize themselves with mechanical operations fail to appreciate the significance of many details of shop technique in the manufacture of serviceable material. There are other persons who regard the requirements for physical and chemical tests as being, collectively, a satisfactory index to the suitability of what is purchased. In some such cases, foundrymen have regretted the wrong sense of proportion exhibited by representatives of buyers. As specification making becomes (as it might) more of a fine art than it is now, and takes on the characteristics of specialization somewhat comparable with what has developed in casting manufacture, authoritative purchase requirements should be more satisfactory than they are now to the conscientious producer, and to the consumer whose needs justify him in using every reasonable method to obtain a quality product especially adapted to his use. When this condition prevails, probably details of shop practice will be covered in specification clauses which are not now included in them, primarily because the present specifications are intended to cover a wide range of products.

For the interests of all concerned, it is hoped that as specifications may ultimately be made more elaborate, they will at the same time be brought into conformity with each other, in so far as this is feasible. Specifically, and for the sake of example, such a condition as the author hopefully anticipates would establish identical physical and chemical limits for such specifications as may govern purchases of differing products, made from one grade of steel and heat treated by a given method. Obviously, any other procedure works to the disadvantage of the producer. And any such handicap, ultimately, is passed on to the consumer.

For the purpose of enabling consumers to acquaint themselves with steel-foundry conditions that influence the satisfactoriness of a product, purchasers of steel castings can well afford to take advantage of opportunities freely accorded them by progressive manufacturers to explain details of shop practice that are not covered in specifications, but which are essential, and may at some time in the future, in part, be covered by clauses in specifications for this cast product that has unsurpassed flexibility. The author means, by the use of this word, to indicate the very great range in physical properties peculiar to what is made in the steel foundry. As manufacture of cast alloy steels becomes more extended, the industry is bound to become increasingly specialized. That will automatically lead to a greater number of recognized specifications, each containing requirements pertinent to its class of product. It is greatly to be desired that consumers become well informed regarding the subject of this paper before participating in those future efforts at specification writing along specialized lines which the author anticipates.

SPECIFICATIONS

Before summarizing the principal requirements in those specifications for steel castings that have received rather general attention after adoption, it seems advisable to make some explanations regarding requirements sponsored by the American Society for Testing Materials. And it is appropriate to mention that a mutually satisfactory, cooperative arrangement prevails, through which both the American Foundrymen's Association and the Steel Founders' Society of America have official representation on those committees of the Society dealing with specifications for steel castings.

The term "tentative standard" as used by the Society applies to a specification of such apparently satisfactory character as to justify trial, prior to adoption as a standard. A standard, finally adopted, implies the belief that, after a probationary period, the specification has been found satisfactory for use, pending developments in manufacture or in testing, which may subsequently justify revision.

There are now five specifications for steel castings which bear the endorsement, in some form, of the American Society for Testing Materials. It first undertook to prepare specifications for steel castings in 1900. The purchase requirements then proposed were adopted in 1901. The specifications were continued as standard without revision until 1905. By that time the practice of annealing steel castings had become more prevalent than it was previously, and the requirement relating to this operation was made to read: "Castings to be annealed unless otherwise specified." Previously the clause read thus: "Castings to be annealed or unannealed, as specified."

In the first steel casting specification adopted by the Society, provision was made for three classes, hard, medium and soft. Carbon steel, not designated by name as such, was the grade covered, exclusively. The tensile requirements were as follows:

	HARD CASTINGS	MEDIUM CASTINGS	SOFT CASTINGS
Tensile strength, lb. per sq. in.....	85 000	70 000	60 000
Yield point, lb. per sq. in.........	38 250	31 500	27 000
Elongation in 2 in., per cent.......	15	18	22
Contraction of area, per cent......	20	25	30

The chemical requirements were confined to a maximum limit of 0.05 per cent both for phosphorus and for sulfur.

Due to the growing tendency to specialize in the manufacture of steel castings, there are now four A.S.T.M. specifications for carbon-steel castings and one for alloy steel castings, the latter covering austenitic-manganese, or Hadfield's manganese steel. With this preliminary explanation of the Society's method of procedure and identification, and the inception of specifications for steel castings, the condensed information in what follows, relating to three standard and two tentative specifications of the Society now in effect, will be self-explanatory.

A.S.T.M. SPECIFICATIONS

A.S.T.M. STANDARD SPECIFICATIONS FOR CARBON-STEEL CASTINGS: A 27 – 24[1]

(Specifications for material of carbon steel for general service and for ships.)

Classes: 2 in number; class A, castings not heat treated, for which no physical requirements are specified; class B, castings heat treated, for which there are physical requirements, varying according to hard, medium, and soft grades.

Chemical requirements:

	CLASS A	CLASS B
Carbon, per cent	not over 0.45	not specified
Phosphorus, per cent		
Acid	not over 0.07	not over 0.06
Basic	not over 0.06	not over 0.05
Sulfur, per cent	not specified	not over 0.06

Tension tests: For class B castings only. (Minimum values.)

	HARD	MEDIUM	SOFT
Tensile strength, lb. per sq. in	80 000	70 000	60 000
Yield point, lb. per sq. in., percentage of tensile strength	45	45	45
Elongation in 2 in., per cent	17	20	24
Reduction of area, per cent	25	30	35

Bend tests: For castings intended for general service, of medium and soft grades, only when specified in the order; not required for castings for general service, of hard grade; required for certain castings for ships. Specimen 1 by ½ in. in section to bend cold without cracking on outside of bent portion, around pin 1 in. in diameter, to following angles: Medium, 90 deg.; soft, 120 deg.

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[1] 1930 Book of A.S.T.M. Standards, Part I, p. 227.

A.S.T.M. STANDARD SPECIFICATIONS FOR CARBON-STEEL CASTINGS FOR VALVES, FLANGES, AND FITTINGS FOR HIGH-TEMPERATURE SERVICE: A 95 - 29[1]

(Specifications for material subjected to temperatures up to 750° F., 400° C.)

Chemical requirements:

Carbon, per cent	0.15 to 0.45
Manganese, per cent	not under 0.50
Silicon, per cent	not under 0.20
Phosphorus, per cent	not over 0.05
Sulfur, per cent	not over 0.06

Tension tests (minimum values):

Tensile strength, lb. per sq. in.	70 000
Yield point, lb. per sq. in.	36 000
Elongation in 2 in., per cent	22
Reducation of area, per cent	30

Bend tests: Only when specified in the order. Specimen 1 by ½ in. in section to bend cold without cracking on outside of bent portion, around pin 1 in. in diameter, to angle of 90 deg.

A.S.T.M. STANDARD SPECIFICATIONS FOR CARBON-STEEL CASTINGS FOR RAILROADS: A 87 - 27[2]

Grades: 2 in number; grade A, special castings not heat treated, and other castings heat treated, all subject to ordinary stresses for which reasonably soft steel is suitable; and grade B, castings heat treated, including those for high stresses justifying harder metal than that employed for some railroad purposes.

Chemical requirements:

(For Grades A and B)

Manganese, per cent	not over 0.85
Phosphorus, per cent	not over 0.05
Sulfur, per cent	not over 0.05

Tension tests (minimum values):

	GRADE A		GRADE B
	NOT HEAT TREATED	HEAT TREATED	HEAT TREATED
Yield point, lb. per sq. in.	29 250	29 250	36 000
Elongation in 2 in., per cent	$\frac{1\ 450\ 000}{\text{Tens. str.}}$	$\frac{1\ 600\ 000}{\text{Tens. str.}}$	$\frac{1\ 600\ 000}{\text{Tens. str.}}$
but not less than	22	24	22
Reduction of area, per cent	$\frac{2\ 250\ 000}{\text{Tens. str.}}$	$\frac{2\ 600\ 000}{\text{Tens. str.}}$	$\frac{2\ 500\ 000}{\text{Tens. str.}}$
but not less than	30	35	30

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[1] 1930 Book of A.S.T.M. Standards, Part I, p. 264.

[2] *Ibid.*, p. 232.

A.S.T.M. TENTATIVE SPECIFICATIONS FOR ELECTRIC CAST-STEEL STUD-LINK ANCHOR CHAIN: A 77 – 28 T[1]

Physical requirements: Proof and breaking tests only, to conform to service conditions to which chains are subjected. (These tests, specified in detail, require equipment especially suited for this purpose; and differ from physical tests to which specimens representing other ferrous castings are subjected. The proof and breaking tests are not supplemented by other physical tests.)

NOTE: Metal for cast-steel anchor chain is subject to no chemical requirements.

A.S.T.M. TENTATIVE SPECIFICATIONS FOR AUSTENITIC MANGANESE-STEEL CASTINGS: A 128 – 30 T[2]

(Material sometimes referred to as Hadfield's manganese steel.)

Chemical requirements:

Carbon, per cent	1.00 to 1.40
Manganese, per cent	10.00 to 14.00
Phosphorus, per cent	not over 0.10

Bend tests: Only when specified in the order. Specimen 12 by $\frac{3}{4}$ by $\frac{1}{2}$ in. to bend cold without breaking, around pin 1 in. in diameter, to angle of 150 deg.

NOTE: No tension tests required.

NATIONALLY APPLIED SPECIFICATIONS

U. S. GOVERNMENT MASTER SPECIFICATIONS NO. 170 FOR STEEL CASTINGS

(Officially Promulgated June 30, 1924)

Grades: Special, hard, medium, soft, and common.

Chemical requirements (maximum percentages):

GRADE	CARBON	MANGANESE	SILICON	PHOSPHORUS	SULFUR
Special	as required				
Hard	0.50	....	....	0.05	0.06
Medium	0.45	....	....	0.05	0.06
Soft	0.35	....	....	0.06	0.06
Common	0.45	0.80	0.40	0.07	0.08

Tension tests (minimum values):

GRADE	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
Special	as required			
Hard	80 000	45 per cent of tensile strength	17	25
Medium	70 000		20	30
Soft	60 000		24	35
Common	none required			

Bend tests: 120 deg. for both medium and soft grades; none for hard and common grades; as required for special grade. Bend test specimen about 6 in. long, with cross-section of 1 by $\frac{1}{2}$ in., to be bent around pin 1 in. in diameter without cracking an outside of bent portion.

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part I, p. 702 (1928); also 1931 Book of A.S.T.M. Tentative Standards, p. 70.

[2] *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part I, p. 969 (1930); also 1931 Book of A.S.T.M. Tentative Standards, p. 80.

U. S. ARMY SPECIFICATIONS NO. 57-64 A FOR STEEL CASTINGS

(Revised July 23, 1924)

Grades: Numbers 0, 1, 2, 3, and 4.

Chemical requirements (maximum percentages):

GRADE	CARBON	MANGANESE	SILICON	PHOSPHORUS	SULFUR
0	0.45	0.80	0.40	0.07	0.08
1	0.35	....	....	0.06	0.06
2	0.45	....	....	0.05	0.06
3	0.50	....	....	0.05	0.06
4			as specified		

Tension tests (minimum values):

GRADE	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
0		none required		
1	60 000	45 per cent of tensile strength	24	35
2	70 000		20	30
3	80 000		17	25
4		as specified		

Bend tests: 120 deg. for both grades 1 and 2; none for grades 0 and 3; as specified for grade 4. Bend test specimen 6 to 8 in. long, with cross-section of 1 by ½ in., to be bent around pin 1 in. in diameter without cracking on outside of bent portion.

U. S. NAVY DEPARTMENT SPECIFICATIONS NO. 49SLG

(Revised April 1, 1925)

Classes: F, A, D, B, and C.

Chemical requirements (maximum percentages):

CLASS	CARBON	MANGANESE	SILICON	PHOSPHORUS	SULFUR
F		....	....	0.05	0.05
A	0.50	....	....	0.05	0.06
D	0.45	....	....	0.05	0.06
B	0.35	....	....	0.06	0.06
C	0.45	0.80	0.40	0.07	0.08

Tension tests (minimum values):

CLASS	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
F	85 000	53 000	22	35
A	80 000	45 per cent of tensile strength	17	25
D	70 000		20	30
B	60 000		24	35
C		none required		

Bend tests: 120 deg. for classes F, D, and B; none for classes A and C. Bend test specimen about 6 in. long, with cross-section of 1 by ½ in., to be bent around pin 1 in. in diameter, without cracking on outside of bent portion.

U. S. Navy Department Specification for Stud-Link Cast-Steel Chain

Chemical requirements: None.

Tension tests (minimum values):

Tensile strength, lb. per sq. in.	100 000
Yield point, per cent of tensile strength	60
Elongation, in 2 in., per cent	10
Reduction of area, per cent	18

U. S. Steamboat Inspection Service Specifications for Steel Castings

(Published by Department of Commerce in 1929)

Classes: A and B; class A having no physical requirements or annealing treatment required; class B required to have annealing treatment and to show prescribed physical properties.

Chemical requirements (maximum percentages):

Class	Carbon	Phosphorus	Silicon
A	0.45	0.07 (for acid) 0.06 (for basic)	....
B	....	0.05 (for acid) 0.04 (for basic)	0.05

Tension tests (minimum values):

Yield point, lb. per sq. in.	29 250
Elongation, per cent	$\frac{1\,600\,000}{\text{Ten. str.}}$
but not less than	24 per cent
Reduction of area	$\frac{2\,600\,000}{\text{Tens. str.}}$
but not less than	35 per cent

U. S. Steamboat Inspection Service Specifications for Carbon-Steel Castings for Valves, Flanges and Fittings for High-Temperature Service

(Published by Department of Commerce in 1929)

These requirements, chemical and physical, are identical with those in A.S.T.M. Specifications A 95 – 29, abstracted in this paper.[1] It should be noted that the Steamboat Inspection Service has two sets of purchase requirements for carbon-steel castings, and that the first set, abstracted in the foregoing, obviously, is not to govern the purchase of valve castings.

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[1] See p. 93.

AMERICAN BUREAU OF SHIPPING SPECIFICATIONS FOR STEEL CASTINGS
(Issued 1930)

Classes: Hull castings and machinery castings of grades 1 and 2.

Chemical requirements: None.

Tension tests:

	TENSILE STRENGTH, LB. PER SQ. IN.		YIELD POINT, LB. PER SQ. IN.	ELONGATION, PER CENT
Hull	58 000 min.	78 400 max.		20 to 15
Machinery No. 1	58 000 min.	68 000 max.	45 per cent of tensile strength	23 to 20
Machinery No. 2	68 000 min.	78 000 max.		20 to 17

Bend tests: 120 deg. for all varieties. Bend test specimen about 8 in. long, with cross-section of 1 by ¾ in., to be bent around pin 1 in. in diameter without cracking on outside of bent portion.

CANADIAN ENGINEERING STANDARDS ASSOCIATION (C.E.S.A.) STANDARD SPECIFICATION FOR CARBON-STEEL CASTINGS
(Issued May, 1929)

Varieties: Class A (no physical tests) and class B (hard, medium, and soft grades).

Chemical requirements (maximum percentages):

	CARBON	PHOSPHORUS	SULFUR
Class A	0.45	0.07 (acid) 0.06 (basic)	....
Class B	....	0.06 (acid) 0.05 (basic)	0.06

Tension tests (minimum values, class B only):

GRADE	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION, PER CENT	REDUCTION OF AREA, PER CENT
Hard	80 000	45 per cent of tensile strength	17	25
Medium	70 000		20	30
Soft	60 000		24	35

Bend tests: Only when specified in the order. Specimen having cross-section of 1 by ½ in. to be bent 90 deg. for medium grade, 120 deg. for soft grade, around pin 1 in. in diameter without cracking on outside of bent portion. Bend tests not applicable to hard grade in class B or to class A.

BRITISH ENGINEERING STANDARDS ASSOCIATION (B.E.S.A.) STANDARD SPECIFICATION No. 5028-1924 FOR STEEL CASTINGS FOR AUTOMOBILES
(Issued April, 1924)

Grades: Numbers 1 and 2.

Chemical requirements:

	CARBON, PER CENT	MANGANESE, PER CENT	PHOSPHORUS, PER CENT	SULFUR, PER CENT
Grade 1	0.30 max.	0.40 min.	0.05 max.	0.06 max.
Grade 2	0.30 max.	0.60 min.	0.07 max.	0.08 max.

Tension tests (minimum values):

	TENSILE STRENGTH, TONS PER SQ. IN.	ELONGATION, PER CENT
Grade 1	26	20
Grade 2	26	15

B.E.S.A. STANDARD SPECIFICATION NO. 10-30-1907 FOR STEEL CASTINGS FOR MARINE PURPOSES

(Issued June, 1907)

Grades: A, B, C, and D.
Chemical requirements: None.

Tension tests (none required for grade D):

	TENSILE STRENGTH, TONS PER SQ. IN.	ELONGATION, PER CENT
Grade A	35 to 40	15 min.
Grade B	26 to 35	20 min.
Grade C	26 to 35	15 min.

Bend tests (none required for grade D):

Specimen 1 by ¾ in. in cross-section; 60 deg. for grade A, 120 deg. for grade B, 90 deg. for grade C; specimen to be bent around 1-in. pin without fracture.

B.E.S.A. STANDARD SPECIFICATION NO. 10-1930 FOR RAILWAY ROLLING STOCK MATERIAL

(Revised September, 1930)

Classes: A (general castings), B (wheel centers), C (large or important castings).

Chemical requirements (for all classes):

Phosphorus, per cent	0.06 max.
Sulfur, per cent	0.06 max.

Tension tests:

	TENSILE STRENGTH, TONS PER SQ. IN.	ELONGATION, PER CENT
Castings with wearing surfaces	35 to	15
	40	10
	Over 40	10
Other general castings and wheel centers	26	20

Bend tests (for all except castings with wearing surfaces):

Specimen 1 in. in diameter to be bent 120 deg. around bar 2½ in. in diameter without fracture.

B.E.S.A. STANDARD SPECIFICATION NO. 150-1922 FOR CAST STEEL WHEEL CENTERS FOR ELECTRIC TRAMWAY CARS

(Issued April, 1922)

Chemical requirements: None.

Tension tests:

Tensile strength, tons per sq. in	33
Elongation, per cent	10

TENTATIVE AUSTRALIAN STANDARD SPECIFICATIONS NO. E 7–1925 T FOR STEEL CASTINGS

Classes: Class A (general castings), class B (wheel centers), and class C (large or important castings).

Chemical requirements (for all classes):

Phosphorus, per cent	0.07 max.
Sulfur, per cent	0.07 max.

Tension tests:

	TENSILE STRENGTH, TONS PER SQ. IN.	ELONGATION, PER CENT
Castings with wearing surfaces	35	10
Other general castings and wheel centers	26	20

Bend tests (for all except castings with wearing surfaces):

Specimen 9 in. long, 1 in. in diameter, to be bent 90 deg. around bar 2½ in. in diameter without fracture.

AMERICAN RAILROAD SPECIFICATIONS

(Mention is here made, of some requirements that differ from those in A.S.T.M. specifications.)

PENNSYLVANIA RAILROAD CO.

Specifications No. 36-F (March 30, 1931) for Steel Castings; for unannealed and annealed classes of grade A, for grade B (annealed), and for grade C (annealed or normalized). Requirements for grades A and B identical with those for same grades in A.S.T.M. Specifications A 87 - 27, abstracted in this paper.[1]

Chemical requirements.—For grade C restricted to 0.05 per cent maximum both for phosphorus and for sulfur.

Tensile requirements.—For grade C (minimum); yield point, 55,000 lb. per sq. in.; tensile strength, 85,000 lb. per sq. in.; elongation, 22 per cent; reduction of area, 40 per cent.

ST. LOUIS & SAN FRANCISCO RAILWAY CO.

Specification No. 1179 (January 13, 1930) for Chromium-Nickel Steel Castings.

Chemical requirements:

	MINIMUM	MAXIMUM
Carbon, per cent	0.30	0.45
Manganese, per cent	0.50	0.85
Silicon, per cent	0.20	0.40
Chromium, per cent	0.60	1.00
Nickel, per cent	1.25	2.00
Phosphorus, per cent	....	0.05
Sulfur, per cent	....	0.06

Tension test requirements, minimum.—Yield point, 65,000 lb. per sq. in.; tensile strength, 100,000 lb. per sq. in.; elongation, 18 per cent; reduction of area, 30 per cent.

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[1] See p. 93.

Norfolk & Western Railway Co.

Specification 105-C (March 15, 1924) for Carbon Vanadium Cast Steel Locomotive Frames.

Chemical requirements:

Carbon, per cent	0.25 to 0.40
Manganese, per cent	0.60 to 0.85
Vanadium, per cent	not under 0.16
Chromium, per cent	not over 0.25
Phosphorus, per cent	not over 0.05
Sulfur, per cent	not over 0.05

Tension test requirements, minimum.—Yield point, 50,000 lb. per sq. in.; tensile strength, 80,000 lb. per sq. in.; elongation, 20 per cent; reduction of area, 40 per cent.

Erie Railroad Co.

Specification No. 795 (August 6, 1926) for High Tensile Cast Steel Castings.

Chemical requirements:

Carbon, per cent	not less than 0.25
Manganese, per cent	not less than 1.25
Phosphorus, per cent	not over 0.05
Sulfur, per cent	not over 0.05

Tension test requirements, minimum.—Elastic limit, 55,000 lb. per sq. in.; tensile strength, 95,000 lb. per sq. in.; elongation, 22 per cent; reduction of area, 40 per cent.

Erie Railroad Co. (and associated roads)

Specification No. 360-C (November 13, 1911) for Vanadium Steel Castings.

Chemical requirements.—Restricted to minimum of 0.16 per cent vanadium, and maximum of 0.045 per cent both for phosphorus and for sulfur.

Tension test requirements, minimum.—Elastic limit, 50 per cent of tensile strength; tensile strength, 75,000 lb. per sq. in; elongation, 20 per cent.

Bend test requirement.—Specimen 1 by ½ in. in cross-section to be bent 150 deg. without showing defect.

Dynamic test requirement.—Four specimens ⅜ in. in diameter, to average at least 1250 alternating impacts before fracture, in Landgraf-Turner alternating impact machine or its equivalent.

Chesapeake & Ohio Railway Co. (and associated roads—Erie, N. Y. C. & St. L., and Pere Marquette)

Standard Material Specification No. 18 (October 19, 1931) for Heat Treated Alloy Steel Castings.

Chemical requirements.—Restricted to 0.05 per cent maximum both for phosphorus and for sulfur.

Tensile requirements (minimum).—Yield point, 60,000 lb. per sq. in.; tensile strength, 90,000 lb. per sq. in.; elongation, 25 per cent; reduction of area, 50 per cent.

CHESAPEAKE & OHIO RAILWAY CO. (AND ASSOCIATED ROADS)

Material Specification No. 2 (January 17, 1930) for Nickel Steel Castings.

Chemical requirements:

Carbon, per cent	0.10 to 0.20
Manganese, per cent	0.70 to 1.00
Nickel, per cent	2.00 min.
Phosphorus, per cent	0.045 max.
Sulfur, per cent	0.045 max.

Tension test requirements, minimum.—Yield point, 50,000 lb. per sq. in.; elongation, 25 per cent; reduction of area, 45 per cent.

ILLINOIS CENTRAL RAILROAD CO. AND YAZOO & MISSISSIPPI VALLEY RAILROAD CO.

Specification No. 3-L (June 1, 1925) for Locomotive Frames.

Chemical requirements:

Carbon, per cent	not over	0.35
Vanadium, per cent	not under	0.16 (0.20 desired)
Phosphorus, per cent	not over	0.04
Sulfur, per cent	not over	0.04

Tension test requirements, minimum.—Yield point, 40,000 lb. per sq. in.; tensile strength, 75,000 lb. per sq. in.; elongation, 20 per cent; reduction of area, 40 per cent.

CANADIAN PACIFIC RAILWAY CO.

Specification No. 33-A (March 16, 1926) for Nickel Steel Locomotive Main Frames and Splices.

Chemical requirements:

Carbon, per cent	0.20 max.
Manganese, per cent	0.40 to 1.00
Nickel, per cent	2.00 min.
Phosphorus, per cent	0.05 max.
Sulfur, per cent	0.05 max.

Tension test requirements, minimum.—Yield point, 45,000 lb. per sq. in.; elongation, 25 per cent; reduction of area, 45 per cent.

CANADIAN PACIFIC RAILWAY CO.

Tentative Specification No. 24 (March 12, 1928) for Nickel Steel Castings.

Chemical requirements:

Carbon, per cent	0.25 max.
Manganese, per cent	0.90 max.
Nickel, per cent	2.00 min.
Phosphorus, per cent	0.05 max.
Sulfur, per cent	0.05 max.

Tension test requirements, minimum.—Yield point, 50,000 lb. per sq. in.; elongation, 25 per cent; reduction of area, 45 per cent.

AMERICAN INDUSTRIAL CONSUMERS' SPECIFICATIONS

(Mention is here made of some requirements that differ from those in A.S.T.M. specifications.)

STANDARD OIL DEVELOPMENT CO.

Standard Specification No. 9 (December 30, 1931) for Carbon Steel and Chromium-Nickel Steel Castings.

Chemical requirements:

	CARBON STEEL	CHROMIUM-NICKEL STEEL
Carbon, per cent	0.15 to 0.45	0.25 to 0.50
Manganese, per cent	0.50 to 0.85	0.45 to 0.75
Silicon, per cent	0.20 to 0.50	0.20 to 0.45
Chromium, per cent	....	0.65 to 0.95
Nickel, per cent	....	1.75 to 2.25
Phosphorus, per cent	0.05 max.	0.05 max.
Sulfur, per cent	0.05 max.	0.05 max.

Tension test requirements.—For carbon steel, identical with those in A.S.T.M. Specifications A 95 - 29, abstracted in this paper.[1] Tension test requirements for chromium-nickel steel, minimum; yield point, 65,000 lb. per sq. in.; tensile strength, 100,000 lb. per sq. in.; elongation, 18 per cent; reduction of area, 30 per cent.

Bend test requirements.—For specimen 1 by ½ in. in cross-section; 90 deg. for carbon steel, 75 deg. for chromium-nickel steel, around pin 1 in. in diameter, without cracking on outside of bent portion.

STANDARD OIL DEVELOPMENT CO.

Tentative Specification No. 10 (May 14, 1931) for Five per cent Chromium Alloy Steel Castings.

Chemical requirements:

Carbon, per cent	0.15 to 0.35
Manganese, per cent	0.45 to 0.75
Silicon, per cent	0.20 to 0.50
Chromium, per cent	4.00 to 6.50
Molybdenum, per cent	0.40 to 0.65
or	
Tungsten, per cent	0.80 to 1.25
Phosphorus, per cent	0.05 max.
Sulfur, per cent	0.05 max.

Tension test requirements, minimum.—Yield point, 75,000 lb. per sq. in.; tensile strength, 110,000 lb. per sq. in.; elongation, 18 per cent; reduction of area, 30 per cent.

Bend test requirement.—For specimen 1 by ½ in. in cross-section; 90 deg. around pin 1 in. in diameter, without cracking on outside of bent portion.

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[1] See p. 93.

GULF REFINING CO.

Specification P-105-R 1 (December 23, 1931) for Cast Chrome-Tungsten Steel Pipe Fittings:

Chemical requirements:

Carbon, per cent	0.15 to 0.22
Manganese, per cent	0.50 max.
Silicon, per cent	0.50 max.
Chromium, per cent	5.00 to 6.00
Tungsten, per cent	0.80 to 1.25
Phosphorus, per cent	0.05 max.
Sulfur, per cent	0.05 max.

Tension test requirements, minimum.—Yield point, 100,000 lb. per sq. in.; tensile strength, 120,000 lb. per sq. in.; elongation, 18 per cent; reduction of area, 50 per cent.

Hardness test requirement.—Uniform Brinell hardness value of from 225 to 250.

THE TEXAS COMPANY

Specifications (January 24, 1928) for High Pressure and High Temperature Cast Alloy Steel Valves.

Chemical requirements:

Carbon, per cent	0.25 to 0.45
Manganese, per cent	0.50 to 0.70
Silicon, per cent	0.20 to 0.45
Nickel, per cent	2.00 min.
Chromium, per cent	0.75 to 1.00
Phosphorus, per cent	0.05 max.
Sulfur, per cent	0.05 max.

Tension test requirements, minimum.—Yield point, 75,000 lb. per sq. in.; tensile strength, 100,000 lb. per sq. in.; elongation, 18 per cent; reduction of area, 40 per cent.

INTERNATIONAL HARVESTER CO.

Specification (December 28, 1927) for Steel Castings. Annealed and unannealed classes in soft, medium, and hard grades.

Chemical requirements.—Restricted to maximum of 0.06 per cent for phosphorus and for sulfur.

Physical test requirements, minimum:

		TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN. (45 PER CENT OF TENSILE STRENGTH)	ELONGATION, PER CENT	REDUCTION OF AREA, PER CENT	BEND, DEG.
Soft	Annealed	63 000	28 400	24	35	120
	Unannealed	70 000	31 500	15	20	...
Medium	Annealed	73 000	32 800	20	30	90
	Unannealed	80 000	36 000	12	15	...
Hard	Annealed	82 000	37 300	17	25	...
	Unannealed	90 000	40 500	8	10	...

Bend test specimen 10 by 1 by ½ in., to be bent around pin 1 in. in diameter. Required curvature to be made without cracking specimen on outside of bent portion.

M. W. KELLOGG CO.

Specification No. C-1 (September 27, 1927) for Carbon Steel Castings.

Chemical requirements:

Carbon, per cent	0.22 to 0.28
Manganese, per cent	0.50 to 0.70
Silicon, per cent	0.20 to 0.40
Phosphorus, per cent	0.05 max.
Sulfur, per cent	0.05 max.

Tension test requirements.—Identical with those in A.S.T.M. specifications A 95 - 29, abstracted in this paper.[1]

The condensed information that has been given regarding requirements that differ from those in A.S.T.M. specifications includes selected data on carbon-steel and alloy-steel castings. Such data are not presented with the idea of recommending them in whole or in part. Some conform, others conflict with principles underlying specifications for steel castings, in which the author believes. He has stated his convictions regarding certain chemical limitations. In doing this, the author has tried to point out the undesirability of low limits for silicon and manganese. It seems desirable to supplement these comments by mention of narrow limits for carbon. It will be observed that one specification that has been abstracted by the author, who regards the requirements as very improper, prescribes low limits for silicon and manganese, as well as a very narrow range for carbon content. In contrast with this specification, another one, for alloy-steel castings, has been abstracted in the preceding matter, which commendably affords the producer the opportunity to select his preferred chemical composition (excepting for maximum limits for phosphorus and sulfur), for providing the tensile properties desired by the consumer.

With reference to the matter of a narrow carbon range, it seems appropriate to point out the failure of some purchasers to appreciate prevailing circumstances. Bars, plates, and other rolled materials regularly are segregated and placed in warehouses according to the several frequently desired percentages of carbon contained. Consequently, the melter is enabled to deliver the steel without serious penalty even though the carbon content is not found within a narrow range. The result is merely a classification for storage purposes.

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[1] See p. 93.

The steel foundryman occupies a very different position. Generally his product is usable only by one consumer. Despite the melter's skill, a heat may be found to contain a few points of carbon more or less than called for in a narrow range in an unwisely formulated specification. Rejection means that the castings go into the scrap pile. There is no opportunity for stocking the material according to grades of carbon content. Eventually, consumers who buy steel castings in this way have to pay prices commensurate with the restrictive nature of their purchasing policies.

Mention has been made of the fallacy of gaging the influence of any single element, excepting in relation to the proportions of other elements. If this metallurgical factor is kept in mind, and if a proper sense of proportion actuates buyers (not according to restrictive conditions of composition, but according to the properties that affect serviceability) important economies accompanied by satisfactory performance of the material should result.

It is the hope of the author that this paper will be found helpful to those who use steel castings and who desire to know more than they have known about the requirements that have governed purchases of this product. The author also hopes the data given will prove to be a convenient summary for use by his colleagues in the steel-casting industry.

DISCUSSION

MR. H. H. LESTER[1] (*by letter*).—Mr. Bull has taken a definite stand that test coupons should be cast separately, or in such manner as to insure the best possible metal in the coupons. The writer is in complete agreement with this view, with the provision that the test coupon should be made to represent the metal in the average or in the thickest section of the casting. The effect of mass should be considered in the coupon.

Tests from test coupons give values only for the coupons. As Mr. Bull has shown, they are not reliable as indications of the physical properties in the casting, and may in fact be misleading to engineers inclined to take them too seriously. The same can be said for specimens taken from the wall of the casting. We have seen specimens fail miserably while specimens taken an inch or two away passed easily.

There arises the question, how can cast metal be judged? It seems to the writer that coupon or other physical tests are essential as defining the possible strength of the metal when sound. If in addition X-ray or other tests were applied to test soundness, there would result a much better picture.

Of course, results from tests of coupon metal would have to be evaluated in terms of relative soundness, and estimates of casting strength would have to be made with due regard to location and distribution of defects.

In spite of great improvement in the quality of cast steel during recent years, there is a great deal of room for further improvement, particularly in the matter of homogeneity. If the characteristics in the casting can be brought up to the quality of those in the test coupon, engineers will gain a new respect for the product of the steel foundry.

MR. BRADLEY STOUGHTON.[2]—Mr. Bull has brought out a great many facts. He has compared them and has made out a case showing the desirability of reasonable restrictions. There is altogether too much tendency on the part of purchasers, especially in times like these, to impose their own individual specifications on the manufacturer. If these purchasers would discuss the matter in an open meeting like this, where there could be a general discussion by men interested in getting at the truth rather than in proving some individual point, it seems to me a great deal of good could be done. Some men like to have their own peculiar specifications that differ slightly from others. If opinions regarding such matters could be brought up for general discussion in a meeting like this, we would get a good deal more standardization than we can in any other way. I hope that there may be some users of steel castings here who will express here publicly their objections, if they have any, to some of the very important suggestions Mr. Bull has made.

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[1] Research Physicist, Watertown Arsenal, Watertown, Mass.

[2] Director, Curriculum of Metallurgical Engineering, Lehigh University, Bethlehem, Pa.

MR. F. B. OLCOTT.[1]—Mr. Stoughton's remarks prompt me to take the floor as representing a consumer of steel castings which has been writing specifications for a great many years. However, I have no criticism of Mr. Bull's paper. Our experience would lead us to concur in all of the fundamental points the author has laid down. We believe that you should not tie down the steel foundry by specifying definite limits on chemical composition, physical properties, methods of heat treatment, tests and what not. We agree with Mr. Bull's statement that chemical limits should be specified only for those elements considered as impurities, with a possible indication of certain elements that are necessary when an alloy of a particular type is called for. It is quite reasonable to assume that, in specifying a definite type of nickel steel, the specification might indicate certain reasonable chemical limits of the nickel content, or indicate in some way that a certain nickel steel is required. Having given the foundry the information in a specification regarding the type of alloy desired, and having definitely specified the physical properties required, the purchaser should give the foundry a more or less free hand in determining the desired analysis, taking into consideration the design of the casting, the thickness of the sections, etc., in order to arrive at the physical properties specified.

Mr. Bull's paper showed the wide divergence of requirements in many specifications commonly used. Some of the specifications are so nearly alike that it would take but very little work to make them uniform. Any effort leading to such uniformity would be very beneficial, both to the consuming and to the producing interests.

There have been several references made to the question of design, by Mr. Bull and Mr. Lorenz and in some of the other papers. It is not unexpected to see such stress laid on the design of steel castings. In the past there has been entirely too great a tendency for the designer to take insufficient consideration of the foundry's difficulties in meeting narrowly drawn specifications. I think there has been a disposition in the past several years to reduce that handicap. The movement has not gone far enough, but it probably will as the entire consuming industry becomes educated to the necessity of it. It is papers and discussions such as those presented here that bring those points home. In our work, which has been largely in connection with the production and purchase of large hull castings, we have found that the question of design has been very embarrassing at times. We have had castings designed that were most difficult to turn out in the foundry without serious defects. This has resulted in modification of the design after loss of castings and delay in obtaining replacement material. It very often occurs that a change in the design of a casting, in order to make it easy to cast, can be accomplished with very little work. Frequently a very slight change in section will transform an impossible design to one that is entirely satisfactory from the foundry standpoint. The opinion has been expressed that it might be a good plan to have the designer spend an hour and a half with the foundryman on the design of every casting. I think if a principle like that could be agreed on by all concerned with the production of steel castings, it would go a long way toward eliminating difficulties.

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[1] Senior Materials Engineer, U. S. Navy, Bureau of Construction and Repair, Washington, D. C.

MR. JOHN HOWE HALL.[1]—Of late years a number of foundrymen have encountered a disposition on the part of the consumer to demand that the physical properties of any part of a casting should be, for instance, such as those obtained from a coupon of the type shown in Fig. 1 of Mr. Bull's paper, or the consumer says: "Well, if you cannot make the properties throughout that casting as good as those of a coupon, you should make them perhaps 60 or 70 per cent as good;—we want to draw up a specification which will allow us to use a core drill and trepan a specimen out of any place we choose in that casting, which will meet certain physical requirements." Mr. Bull has brought out very clearly the fact that, even if the casting is 100 per cent sound everywhere, the differences in the rate of cooling between the thick sections and the thin sections are bound to produce differences in grain size which will lead to considerable differences in physical properties between different parts of the casting, but that is only a part of the story. Mr. Lorenz showed a number of typical instances in which a casting will not be sound if certain features of design are incorporated in it. One such case is shown also by Mr. Bull in his Fig. 4 illustrating the effect of the junction of a thick section and a thin section; at that point there is a place where the metal varies not only in crystal size but in actual soundness. I wonder how many purchasers of steel castings realize that they are asking the foundries to produce a great number of castings in which there are areas, such as those shown by Mr. Bull, of such a nature that if the foundry is held down to the design as put forward, there is bound to be actual unsoundness. Naturally, if a test specimen is trepanned out of such a place, the physical properties secured from that test will not be commensurate with those of a coupon. From my own experience in dealing with purchasers, I believe that it is not at all realized to what an extent a great many steel castings cannot, as they are designed, be made actually sound. It is going to help greatly in the education of the consumer that we are now agitating this question of physical properties in these various difficult sections. With core drill specimens, examination by the X-ray and the gamma ray, and other methods of investigation, much progress is being made which is going to help the foundryman to improve his technique in getting sound castings, and I hope it is going to help the consumer a whole lot too, in educating designers to the fact that they are putting up to the foundry designs which are bound to be more or less unsound at various points, so that they will not possess the physical properties the purchaser desires them to show.

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[1] Technical Assistant to President, Taylor-Wharton Iron and Steel Co., High Bridge, N. J.

MR. F. A. LORENZ, JR.[1]—When the making of new specifications is undertaken by the individual producer or a technical society for the trade which it represents, the practical production problems confronting the steel foundry should always be taken into consideration. The average foundry, particularly in these times of low production, operates on a one-furnace basis. All of the steel which is made has to be made in this one furnace. It is not uncommon in the average industrial steel foundry to receive orders during an average production period of a week, which have to meet twenty or thirty specifications covering both the chemical and physical properties of the castings. It is a delicate problem in production to arrange all of the orders so they may be grouped and produced from the two or three heats of steel and yet meet everybody's specifications within practical limitations.

The influence of the quantity desired by each customer to any particular specification in times like these is one of the most serious problems which confronts the steel foundryman. Any consumer has the right to make any reasonable specification he wants for some particular purpose, and sometimes he is willing to pay accordingly, but he usually reserves the right to order 100 lb. or 100,000 lb. from any particular specification at any time. It certainly would be much more to the liking of the average producer to have a few specifications which would meet the various physical requirements. However, there seems to have been a movement among buyers recently to vary their specifications without reference to any organized effort on the part of technical societies to set standard specifications for certain groups of physical requirements. Add to this the difficulty in meeting the quantity requirements and the situation is still further complicated. This is not an expression of dissatisfaction with specifications as such. Most of the specifications can be met in any well organized steel foundry, provided the quantity ordered under any particular specification at one time is sufficient to enable the foundry profitably to prepare enough molds to make a special heat of steel.

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[1] General Manager, Industrial Division, American Steel Foundries, Chicago, Ill.

MR. N. E. WOLDMAN.[1]—I have often raised the question, "What price test coupons?" During my five years' experience in the teaching of practical and theoretical metallurgy, I strongly emphasized the value of rigid test coupon specifications. I insisted that best control over suppliers and best protection for customers could be obtained by demanding that close specifications be rigidly met. The value of test coupons for the check on the quality of steel, the quality of heat treatment, and the physical properties of the finished product was brought to the attention of my students over and over again. But today, after several years of commercial experience and after having rigid specifications thrust on me by our customers, I would take a different stand in teaching the value of test coupons to students.

Test coupons on castings are essential for a check on the cleanliness of the steel, quality of the casting, and chemical analysis. But when the specifications call for definite physical and mechanical properties to be obtained from a test coupon, then the question, "What price test coupons?" arises again. Usually the location of test coupons on castings is left entirely to the foundry, which can cast the coupons vertically, horizontally, from the same feeder or from a separate feeder, near the riser or away from the riser, as integral with the casting or as a prolongation; each method capable of offering different physical and mechanical properties. If the castings are to be supplied annealed, what annealing temperature and time shall the foundry adopt? If the casting sections are massive and the test coupon is standard $1\frac{1}{4}$ by $1\frac{1}{4}$ by 6 in. size, and if the purchaser's inspector is to make standard tension tests of coupons from the castings, then shall the foundry so anneal the casting that specimens from these small coupons will meet the specified properties (with the knowledge that the vital massive sections of the casting proper will be insufficiently annealed), or shall the foundry anneal the casting properly to affect the vital heavy sections, and gamble on the result from the test coupons, which will have a large grain size, caused by the prolonged annealing temperature? In either case the foundry is the loser. If the attached test coupon is properly annealed to meet the specifications, the casting itself is probably insufficiently annealed, and may fail if it is not rejected. If the casting itself is properly annealed (with the probability of over-annealing the test coupon), then the test coupon may not meet the specifications, causing the casting to be rejected. The foundry is subject to the personal interpretation of the value of test coupons by the customer's inspector, purchasing agent or metallurgist, irrespective of the actual quality of the casting, and is subjecting himself to probable unwarranted rejections.

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[1] Metallurgical Engineer, Westinghouse Electric and Manufacturing Co., Materials and Process Engineering Department, East Pittsburgh, Pa.

Now in considering the position of the manufacturers of the finished products, they are endangered by the same misunderstandings and misinterpretations as the foundries. Consider, for example, the manufacturer of large cast-steel gears who is to fabricate the finished gear from the rough casting. He establishes his own specifications, governing the foundry, for the rough casting. All tests will, naturally, be made on the test coupon, and if found satisfactory, the casting will be released for production on the assumption that the casting itself is sound and of good, well annealed steel. After rough turning, finish machining and heat treating, the test bars will be pulled in the presence of the customer's inspectors. These tests must now meet the customer's specifications. Eighty per cent of customers' specifications require that the test coupons be tied to the casting and be heat treated with it. Due to difference in mass between the gear teeth, the gear rim, and the test coupon, the heat treater or metallurgist is at a loss to know whether to heat treat the gear properly and gamble on the gear being rejected, due to the test bar being improperly heat treated and not meeting the specifications, or whether to heat treat so that the test bar will meet the physical properties and gamble on the gear being accepted, but perhaps subsequently failing in service, due to improper heat treatment. Here we may have to worry about three factors: first, the probable rejection or cancellation of the order owing to the fact that the test bar did not meet the specifications, although the gear itself would, if tested; second, the probable loss of the customer due to shattered confidence in the manufacturer; and third, delayed delivery which sometimes results in a monetary penalty.

I believe the only solution to the problem of purchasing requirements is greater cooperation between the purchasing agents and the engineers, and improved standardization. The engineer and the purchasing agent both must recognize the effect of mass on physical properties, in heat treatment. They must realize that it is often not possible to locate a cast-on test bar in a position which will ensure that the affected section is adequately fed during solidification.

MR. R. A. BULL.[1]—It has been pointed out how incorrect it probably is in a good many cases to depend on the conventional clause in a good many specifications, in respect to determining the effect of heat treatment. The examples cited in connection with the gear were extremely interesting. I think such dissimilarities are apt to be shown up in more pronounced fashion as the use of alloy steels becomes more extensive. I am sure that every steel foundryman has often seen fairly large, sometimes very large, sections of castings to which annealing lugs about ¼ in. thick were attached. A great many railroad companies have, in the past, required those lugs to be attached to the casting. The casting goes to the annealer, and after the casting is cold, the inspector with a hammer breaks off this lug—approximately ¼ in. thick—and examines the structure. It looks good, and the casting, which may be five or six inches thick, is assumed to have a good structure.

We all know that heat treatment is a function of time and temperature, and that it takes a good while to properly anneal a very thick casting, so we may be all wrong in many cases where we specify that the test coupon shall be attached to, and be heat treated with the casting. It might be highly desirable to detach the coupon in every case, and give it the proper heat treatment for the properties desired, and give the casting itself the heat treatment it needs, bearing in mind the very important factor of section. Incidentally, all of this is an indirect argument for similarity of section in design, because if you have castings of different sections, you are blocked at the start, if you try to give a differential heat treatment governed by section.

MR. B. F. SHEPHERD.[2]—I wish to say one word in defense of the annealing lug. It is quite true that you often find the annealing lug good and the casting bad, but it is very rarely that you find the annealing lug bad and the casting good.

MR. C. S. KOCH.[3]—In years past, there has frequently been trouble when specifications for both chemical and physical requirements were simultaneously given. This situation has sometimes been a difficult one to overcome. However, recently to make the situation still worse, chemical, physical and Brinell requirements have been asked for at the same time. Recently, we were asked to make chromium-nickel steel at a certain Brinell hardness and with carbon requirements 0.40 to 0.50 per cent, but 0.40 to 0.50 per cent carbon with the chromium as specified would give a very much higher Brinell hardness.

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[1] Director, Electric Steel Founders' Research Group, Chicago, Ill.

[2] Chief Metallurgist, Ingersoll-Rand Co., Phillipsburg, N. J.

[3] President, Fort Pitt Steel Castings Co., McKeesport, Pa.

The point to bring out is that, two are bad enough but now we are getting three qualities to meet, not all of which will "jibe," in every case.

MR. STOUGHTON.—I suppose all steel manufacturers know about the recent pronouncement of two bureaus in Washington, regarding the testing of steel castings by gamma rays; offering to teach manufacturers how to use such rays in testing steel castings. I believe it was hinted that in future, requirements covering this will be included for castings supplied to the Navy Department. That is a real challenge to the manufacturer. Mr. Hall has already said that there are parts of many steel castings which cannot possibly be made right. If all castings will, in future be examined by X-rays or gamma rays, and if Westinghouse and other companies are going to test different parts of the castings instead of testing the coupons, it is a new challenge to the steel castings people.

MR. HALL.—Mr. Stoughton's remarks about the gamma ray and the X-ray in connection with castings, bring up the fact that there is today a very large tonnage of steel castings being made for high-temperature service, particularly in steam power houses, in which every casting is subjected to X-ray inspection, and those in which serious defects are found in vital places are rejected. I am also reminded of an instance in which X-ray inspection was applied to castings by a concern that was both the maker and the consumer of the castings. As many of you remember, the Watertown Arsenal, in the first year or two of their work, told us a whole lot about the efforts they were making to eliminate unsound places in their castings; but after a year or two they got a little more liberal and we learned that they were having great success in putting the porosities in places where they did the least harm!

PHYSICAL AND MECHANICAL PROPERTIES OF SOME WELL-KNOWN CAST STEELS

By C. H. Lorig[1] and C. E. Williams[2]

Introduction

This paper deals with the physical and mechanical properties of the plain carbon, the vanadium, silicon, manganese, copper, nickel, and molybdenum cast steels, and of steels containing various combinations of these alloying elements. Steels of other varieties, including those containing high chromium, are discussed in other papers(**1,2,3**)[3] prepared for this symposium.

The plain carbon cast steels include those which contain from 0.50 to 0.90 per cent manganese, 0.20 to 0.70 per cent silicon, and 0.05 per cent or less of sulfur and phosphorus. They are divided into three classes: the regular grade which contains from 0.22 to 0.35 per cent carbon, the low-carbon grade which contains less than 0.22 per cent carbon, and the high-carbon grade which contains more than 0.35 per cent carbon. In general, this classification follows that recently proposed by Bull(**4**). Steels are included in these groups whose manganese, silicon, sulfur, and phosphorus contents are outside of the limits set, but which obviously belong there.

In reviewing the literature on properties of cast steels, one is struck by the haziness of the data. Few investigations are reported and few are so comprehensive as to include a description of the casting procedure, complete chemical analyses, or a description of the heat-treating procedure, if any, that accompanied the tests. Then too, many of the existing data do not come from tests on commercial products, but instead are obtained from laboratory heats or from test coupons prepared under the most favorable casting conditions and heat treated in accordance with closely regulated laboratory practice. It will not be surprising then, if the properties of some commercial cast steels of a given grade seem to be somewhat inferior to those listed in the subsequent tables.

Low-Carbon Cast Steels

The low-carbon cast steels, of less than 0.22 per cent carbon content, are not made except for special purposes, as better mechan-

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[1] Metallurgist, Battelle Memorial Inst., Columbus, Ohio.

[2] Assistant Director, Battelle Memorial Inst., Columbus, Ohio.

[3] The boldface numbers in parentheses refer to the reports and papers given in the list of references appended to this paper, see p. 193.

TABLE I.—MECHANICAL PROPERTIES AT ROOM TEMPERATURE OF LOW-CARBON STEEL OF 0.09 TO 0.21 PER CENT CARBON CONTENT.

Steel	Chemical Composition, per cent					Mechanical Properties							Treatment of Steel[b]	Investigators
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Impact Values	Hardness[a] Numbers		
No. 1....	0.09	0.47	0.028	0.01	0.02	50 500	....	30 000	31.8	55.8	....	....	1575° F. (855° C.) (3), water quenched, drawn 1200° F. (650° C.) (2), air cooled	Giolitti(5)
						54 500	....	33 700	33.0	60.2	....	....	2000° F. (1095° C.) (14), water quenched. 1575° F. (855° C.) (3), water quenched. Drawn 1200° F. (650° C.) (2), air	
No. 2....	0.11	0.73	0.27	0.027	0.028	56 000	....	38 000	33.0	36.0	....	....	Annealed in commercial furnace	Scharlibbe(6)
No. 3....	0.11	0.60	0.40	0.035	0.030	59 000	26 000	....	13.2	30.0	3.7^c	126 *B*	As cast	Oberhoffer(7)
						57 000	24 000	....	28.2	53.0	2.1^c	119 *B*	1475° F. (800° C.) (6), furnace cooled	
						60 000	35 000	....	29.5	59.5	15.0^c	116 *B*	1650° F. (900° C.) (6), furnace cooled	
						60 000	35 000	....	31.0	54.0	13.7^c	126 *B*	1825° F. (995° C.) (6), furnace cooled	
No. 4....	0.12	0.32	0.25	0.023	0.011	51 000	26 000	25 000	36.2	66.3	4.8^d	....	1650° F. (900° C.) (5), furnace cooled	Körber, Pomp(8)
No. 5....	0.13	0.43	0.52	0.029	0.035	42 000	15 000	....	25.0	40.9	....	90 *B*	As cast	Oberhoffer(7)
						42 000	15 000	....	33.6	64.3	....	90 *B*	1475° F. (800° C.) (6), furnace cooled	
						43 000	26 000	....	34.5	57.4	....	95 *B*	1635° F. (890° C.) (6), furnace cooled	
No. 6....	0.13	0.96	0.36	0.067	0.072	62 000	33 000	....	13.1	14.2	2.94^c	143 *B*	As cast	
						66 000	28 000	....	14.4	43.1	....	....	1475° F. (800° C.) (6), furnace cooled	
						68 000	40 000	....	24.4	40.4	9.39^c	143 *B*	1560° F. (850° C.) (6), furnace cooled	
						68 000	38 000	....	25.0	38.3	7.09^c	141 *B*	1690° F. (920° C.) (6), furnace cooled	
						69 000	35 000	....	25.2	45.8	7.42^c	137 *B*	1825° F. (995° C.) (6), furnace cooled	
No. 7....	0.14	0.45	0.29	0.037	0.016	59 000	34 000	34 000	18.6	28.7	7.4^d	....	1650° F. (900° C.) (5), furnace cooled	Körber, Pomp(8)
No. 8....	0.15	0.81	0.20	....	....	62 000	....	....	34.0	52.5	....	....	Annealed	Melmoth(9)
No. 9....	0.17	0.67	0.23	0.076	0.089	64 000	35 000	35 000	28.5	40.2	3.7^d	....	1650° F. (900° C.) (5), furnace cooled	Körber, Pomp(8)
No. 10...	0.18	0.83	0.30	....	....	73 000	....	....	34.0	49.0	....	....	Annealed	Melmoth(9)
No. 11...	0.20 to 0.25	0.70 to 0.80	0.25 to 0.35	Under 0.03	Under 0.03	67 000	34 000	....	14.0	18.6	15^e	....	As cast	
						70 000	37 000	....	26.5	31.6	36^e	....	1600° F. (870° C.), furnace cooled	
No. 12...	0.19	0.62	0.42	0.05	0.035	76 000	47 000	....	15.0	26.0	....	31 *S*	1625° F. (885° C.), water quenched, drawn 200° F. (95° C.)	Grotts(10)
						73 000	46 000	....	16.0	33.0	....	29.5 *S*	1625° F. (885° C.), water quenched, drawn 800° F. (425° C.)	
						72 000	45 000	....	17.0	36.0	....	29.0 *S*	1625° F. (885° C.), water quenched, drawn 1000° F. (540° C.)	
						71 000	44 000	....	18.0	39.0	....	28.5 *S*	1625° F. (885° C.), water quenched, drawn 1200° F. (650° C.)	
						70 000	42 000	....	19.0	42.0	....	28.0 *S*	1625° F. (885° C.), water quenched, drawn 1400° F. (760° C.)	
						68 000	39 000	....	21.0	46.0	....	27.0 *S*	1625° F. (885° C.), water quenched, drawn 1600° F. (870° C.)	
						66 000	34 000	....	24.0	51.0	....	26.0 *S*	1625° F. (885° C.), water quenched, drawn 1800° F. (980° C.)	
No. 13...	0.19	0.85	0.32	0.024	0.016	68 000	....	43 000	35.0	56.0	....	....	Annealed in commercial furnace	Scharlibbe(6)
No. 14...	0.20	0.73	0.40	....	....	69 000	....	43 000	27.2	39.7	....	....	1650° F. (900° C.), furnace cooled	Hall, Nissen, Taylor(11)
No. 15...	0.20	0.72	0.27	0.03	0.04	70 000	47 000	29 000	26.9	50.9	7.3^f	....	1690° F. (920° C.) (10), furnace cooled	Thum, Holdt(12)
No. 16...	0.20	0.46	0.21	0.033	0.045	69 000	41 000	35 000	26.9	55.7	....	....	85° F. (29° C.) above critical, cooled in Kieselguhr	Körber, Dreyer(13)
No. 17...	0.21	0.57	0.21	0.044	0.038	68 000	45 000	40 000	21.0	60.5	....	....	85° F. (29° C.) above critical, cooled in Kieselguhr	
No. 18...	0.21	0.94	0.19	0.03	0.07	76 000	....	43 000	25.0	33.5	4.6^d	....	As cast	Giolitti(5)
						78 000	....	53 000	27.0	42.0	8.13^d	....	1560° F. (850° C.) (3), cooled slowly	
						80 000	....	56 000	28.0	45.0	9.89^d	....	1560° F. (850° C.), air quenched, drawn 1025° F. (550° C.)	
						81 000	....	56 000	32.0	60.0	17.12^d	....	Forged, 1560° F. (850° C.) (3), cooled slowly	

[a] The letter *B* designates Brinell hardness and the letter *S*, Scleroscope hardness.

[b] Numbers in parentheses correspond to number of hours at temperature.

[c] Values in m-kg. per sq. cm.

[d] Specimen 30 by 30 by 160 mm. Cylindrical notch 4 mm. in diameter, 15 mm. deep. Values in m-kg. per sq. cm.

[e] Izod impact, ft-lb.

[f] Specimen 10 by 10 mm. Notch 2 mm. wide, 5 mm. deep. Value in m-kg. per sq. cm.

ical properties can be obtained with higher carbon content. Except for refinement in grain structure and improvement in ductility, they do not respond readily to heat treatment.

In Table I the mechanical properties at normal temperatures of cast steels containing from 0.09 to 0.21 per cent carbon are tabulated. Although gathered from a broad field of investigations, the results are uniformly consistent. Some doubt might arise concerning the properties of steel No. 5. Oberhoffer(7) could not explain the difference between its properties and those of steel No. 3, but suggested that some relationship might exist between the mechanical properties and the density of the steel. His measurements of the specific gravities of the two steels in the unannealed and annealed states are given below. It is difficult to explain how an increase in specific gravity should adversely affect the mechanical properties of an annealed steel. Further work should be done to determine whether such a relationship actually exists.

	SPECIFIC GRAVITY		
	UNANNEALED	ANNEALED AT 1475° F. (800° C.)	ANNEALED AT 1635° F. (890° C.)
Steel No. 5	7.850	7.825	7.848
Steel No. 3	7.809	7.806	7.811

The terms yield point and elastic limit are used in this paper as interpreted by the investigators whose data appear in the text.

The elongation expressed in per cent over a given gage length requires some explanation. It is customary practice in America to record the elongation over a 2-in. gage length, but some of the German investigators have used gage lengths of 50, 60, 70 and 200 mm. As the values under these conditions are not strictly comparable, the term per cent elongation loses some of its significance. The values are reported as they appeared in the literature and no designation as to gage length is given.

Likewise, the values for impact properties of steel are relative. Specimens varying in cross-sectional dimensions and notch types were used. The values, as given, illustrate the alteration in the ductility of the steel with heat treatment and for this reason are of definite significance, even though they cannot be interpreted in absolute units. German investigators usually express the impact resistance in terms of energy absorbed per unit cross-section of steel. Consequently they have adopted the meter-kilogram per square centimeter as a unit. Since it is known that the impact values depend so greatly upon the specimen dimensions, this unit is not of universal application. American investigators now use either the Izod or Charpy

TABLE II.—PROPERTIES OF LOW-CARBON CAST STEEL AT ELEVATED TEMPERATURES.

Steel	Chemical Composition, per cent					Mechanical Properties	Temperature of Test						
	Carbon	Manganese	Silicon	Sulfur	Phosphorus		70° F. (21° C.)	212° F. (100° C.)	390° F. (200° C.)	480° F. (250° C.)	570° F. (300° C.)	750° F. (400° C.)	930° F. (500° C.)
No. 4. Heated to 1650° F. (900° C.) for 5 hours, furnace cooled.	0.12	0.32	0.25	0.023	0.011	Tensile strength, lb. per sq. in.	51 000	47 000	61 000	....	61 000	41 000	40 000
						Elastic limit, lb. per sq. in.	25 000	22 000	22 000	....	13 000	10 000	7 100
						Yield point, lb. per sq. in.	26 000	24 000	22 000	....	16 000	15 000	11 000
						Elongation, per cent	36.2	33.3	23.3	....	26.2	39.2	53.9
						Reduction of area, per cent	66.3	64.2	54.9	....	55.0	66.5	76.9
						Impact, m-kg. per sq. cm.	4.8	19.3	23.9	....	20.5	16.4	13.7
No. 7. Heated to 1650° F. (900° C.) for 5 hours, furnace cooled.	0.14	0.45	0.29	0.037	0.016	Tensile strength, lb. per sq. in.	59 000	51 000	58 000	....	60 000	54 000	29 000
						Elastic limit, lb. per sq. in.	33 000	26 000	26 000	....	14 000	15 000	9 000
						Yield point, lb. per sq. in.	34 000	27 000	27 000	....	19 000	20 000	14 000
						Elongation, per cent	18.6	19.8	10.5	....	13.5	21.6	25.5
						Reduction of area, per cent	28.7	35.6	22.8	....	21.0	26.5	43.2
						Impact, m-kg. per sq. cm.	7.4	16.1	15.5	....	14.9	10.2	8.5
No. 9. Heated to 1650° F. (900° C.) for 5 hours, furnace cooled	0.17	0.67	0.23	0.076	0.089	Tensile strength, lb. per sq. in.	64 000	62 000	75 000	....	75 000	61 000	43 000
						Elastic limit, lb. per sq. in.	33 000	32 000	32 000	....	24 000	19 000	16 000
						Yield point, lb. per sq. in.	35 000	33 000	32 000	....	26 000	23 000	22 000
						Elongation, per cent	28.5	23.9	16.0	....	23.2	24.9	40.3
						Reduction of area, per cent	40.2	43.7	22.8	....	31.6	37.8	64.2
						Impact, m-kg. per sq. cm.	3.7	10.2	11.2	....	9.8	7.2	5.9
No. 10*a*. Heated to 1650° F. (900° C.) for 5 hours, furnace cooled.	0.18	0.77	0.19	0.043	0.064	Tensile strength, lb. per sq. in.	64 000	61 000	63 000	....	64 000	53 000	35 000
						Elastic limit, lb. per sq. in.	38 000	35 000	33 000	....	19 000	16 000	11 000
						Yield point, lb. per sq. in.	39 000	36 000	33 000	....	25 000	21 000	18 000
						Elongation, per cent	29.6	29.5	22.1	....	21.6	30.8	47.8
						Reduction of area, per cent	51.2	51.3	44.0	....	43.2	49.5	74.8
						Impact, m-kg. per sq. cm.	7.8	12.6	11.9	....	11.4	10.0	7.2
No. 16. Material hot-worked at testing temperatures, specimens elongated approximately 10 per cent.	0.20	0.46	0.21	0.033	0.045	Tensile strength, lb. per sq. in.	74 000	78 000	90 000	92 000	92 000	86 000	....
						Elastic limit, lb. per sq. in.	67 000	74 000	88 000	89 000	90 000	81 000	....
						Yield point, lb. per sq. in.	70 000	76 000	88 000	90 000	90 000	81 000	....
						Elongation, per cent	19.0	14.6	4.6	3.9	4.7	9.3	....
						Reduction of area, per cent	51.3	50.5	45.1	40.9	42.7	44.2	....
No. 16. Material cold-worked and tempered for 5 hours at testing temperatures, specimens elongated approximately 10 per cent.	0.20	0.46	0.21	0.033	0.045	Tensile strength, lb. per sq. in.	75 000	79 000	82 000	80 000	80 000	78 000	....
						Elastic limit, lb. per sq. in.	68 000	75 000	78 000	74 000	73 000	67 000	....
						Yield point, lb. per sq. in.	70 000	75 000	78 000	74 000	73 000	67 000	....
						Elongation, per cent	18.4	12.1	9.9	11.3	12.1	12.0	....
						Reduction of area, per cent	51.3	47.1	48.3	45.2	43.5	45.2	....
						Impact, m-kg. per sq. cm.	7.6	6.8	4.3	3.4	3.7	5.9	....
						Hardness (5-mm. ball, 750-kg. load)	169	172	184	186	187	186	..
No. 17. Material hot-worked at testing temperatures, specimens elongated approximately 10 per cent.	0.21	0.57	0.21	0.044	0.038	Tensile strength, lb. per sq. in.	74 000	78 000	92 000	95 000	85 000	82 000	....
						Elastic limit, lb. per sq. in.	67 000	73 000	85 000	93 000	84 000	75 000	....
						Yield point, lb. per sq. in.	69 000	73 000	85 000	94 000	85 000	75 000	....
						Elongation, per cent	11.8	10.5	4.1	4.2	11.3	11.6	....
						Reduction of area, per cent	51.6	51.1	46.2	38.4	41.3	47.4	....
No. 17. Material cold-worked and tempered for 5 hours at testing temperatures, specimens elongated approximately 10 per cent.	0.21	0.57	0.21	0.044	0.038	Tensile strength, lb. per sq. in.	77 000	80 000	81 000	82 000	82 000	83 000	....
						Elastic limit, lb. per sq. in.	66 000	77 000	77 000	78 000	76 000	72 000	....
						Yield point, lb. per sq. in.	72 000	78 000	77 000	79 000	76 000	72 000	....
						Elongation, per cent	14.9	10.7	9.5	10.3	10.2	12.0	....
						Reduction of area, per cent	50.1	49.0	38.1	48.5	45.8	46.7	....
						Impact, m-kg. per sq. cm.	7.7	7.5	5.9	4.0	5.3	4.3	....
						Hardness (5-mm. ball, 750-kg. load)	171	177	188	192	192	193	....

impact specimen and express the impact value as foot-pounds of energy absorbed for a given size of specimen.

Heat treatment of low-carbon cast steel may consist of a full anneal, a normalize, a quench and draw, or a multiple treatment of some other kind. The properties of this steel ascertained in the tension test are not much different in the "as cast" and in the full annealed, normalized, or quenched and drawn condition. The tensile strengths are about equal and the elastic limit and yield point are sometimes lower for steel in the "as cast" state. The coarse casting structure is of low ductility, but this can be improved by a simple full anneal or a normalizing treatment at from 1600 to 1650° F. (870 to 900° C.). A treatment much below this temperature range is of little benefit. Steels Nos. 3, 6 and 12 in Table I illustrate the change in ductility that follows a simple full-annealing operation. The impact values have been raised as much as 400 per cent.

The quenched-and-drawn steels Nos. 1 and 12 have strength properties that are slightly better than those for the annealed bars. The low-carbon steel castings may be quenched without danger from cracking.

Mechanical Properties of Low-Carbon Steel at Elevated Temperatures:

A few investigations of the mechanical properties at elevated temperatures of the low-carbon cast steels have been reported. Körber and Dreyer(13) studied the effect of cold and hot working on properties of such steels over a temperature range of 70 to 750° F. (21 to 400° C.). The same steels also were aged for many days at 70° F. (21° C.) after they had been cold worked an amount equivalent to 8 to 9 per cent extension. Körber and Pomp(8) determined the mechanical properties of a few steels of this grade over a temperature range of 70 to 930° F. (21 to 500° C.). Results from the two investigations are combined in Table II.

In the annealed steels Nos. 4, 7, 9 and 10*a*, the tensile strength reaches a maximum at temperatures between 400 and 600° F. (205 and 315° C.), whereas neither the elastic limit nor the yield point reaches a maximum above room temperature. The ductility of the steels as represented by the percentage elongation and reduction in area shows a minimum in the temperature interval between 400 and 600° F. (205 and 315° C.). This change in ductility is not so evident from the impact tests. Below the boiling point of water, the impact resistance rapidly drops until at room temperature it is 200 to 400 per cent below its value at 212° F. (100° C.). At high temperatures the impact resistance does not begin to decrease rapidly until the temperature is above 600° F. (315° C.).

When the steels are worked at increasing temperatures, the elastic limit, the yield point and the tensile strength increase with temperature until they reach a maximum at 500 to 600° F. (260 to 315° C.). Corresponding to these changes, the reduction of area and elongation reach a minimum value at 400 to 500° F. (205 to 260° C.) and then increase at higher temperatures.

The cold-worked material heated for one and five hours at increasing tempering temperatures has a maximum elastic limit, yield point and tensile strength at 212° F. (100° C.). The elongation reaches a minimum at 400 to 500° F. (205 to 260° C.). One hour tempering is sufficient to develop the maximum change.

TABLE III.—THE AGING OF COLD-WORKED LOW-CARBON CAST STEEL.

Steel	Chemical Composition, per cent					Time at 70° F. (21° C.)	Mechanical Properties				
	Carbon	Manganese	Silicon	Sulfur	Phosphorus		Tensile Strength, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent
No. 17......... Cold-worked and tempered at 70° F. (21° C.), specimens elongated approximately 10 per cent.	0.21	0.57	0.21	0.044	0.038	1 hour....	75 000	66 000	69 000	11.9	51.6
						5 hours....	77 000	66 000	72 000	14.9	50.1
						1 day.....	77 000	69 000	71 000	17.2	53.1
						5 days....	76 000	70 000	73 000	13.7	51.9
						83 days...	82 000	80 000	81 000	9.5	54.0
No. 16......... Cold-worked and tempered at 70° F. (21° C.), specimens elongated approximately 10 per cent.	0.20	0.46	0.21	0.033	0.045	1 hour....	74 000	67 000	70 000	17.9	49.5
						5 hours....	75 000	68 000	70 000	18.4	51.3
						61 days...	77 000	75 000	75 000	13.6	48.3

The mechanical properties of the aged steel are given in Table III. The aged steel slowly increases in tensile properties and decreases in ductility over a period of three months or more. This change in properties with time is undoubtedly a manifestation of precipitation hardening known to occur in some stressed soft steels.

The Magnetic Properties of Low-Carbon Cast Steel:

The carbon content of cast steels is of importance when they are used in the manufacture of various electrical equipment. Melmoth(9) has shown that the magnetic flux, *B*, is much higher at a given value of magnetic field, *H*, for a steel containing 0.12 per cent carbon than for one with 0.21 per cent carbon. The analyses of the samples are as follows:

	CARBON, PER CENT	SILICON, PER CENT	MANGANESE, PER CENT
Steel M...........................	0.12	0.20	0.40
Steel M1...........................	0.21	0.20	0.65

Both steels were given a straight anneal at between 1560 and 1650° F. (850 and 900° C.), followed by slow cooling. Melmoth's curves are reproduced in Fig. 1.

The change in the ferromagnetic properties with increasing carbon content results from the increase in percentage of cementite. A curve showing the effect of carbon on the hysteresis loss in iron, given by Yensen(14), is reproduced in Fig. 2.

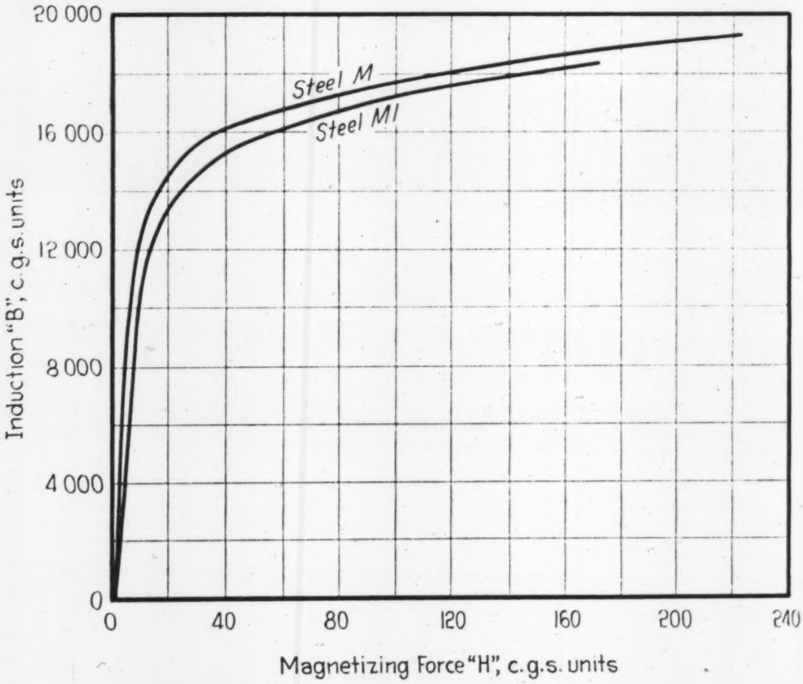

FIG. 1.—Magnetization Curves for Steel Castings.

Manganese, phosphorus, sulfur, and silicon also increase the magnetic hysteresis loss in cast steels. This loss is equal to about 100 ergs per cu. cm. per cycle for $B = 10{,}000$ gausses for each 0.10 per cent manganese, for each 0.01 per cent sulfur, and for each 0.01 per cent phosphorus. Other factors being unchanged, the magnetic hysteresis loss is unaffected by quantities of phosphorus in excess of 0.02 per cent. The effect of silicon is shown in the hysteresis-loss curve for carbon and silicon, Fig. 2.

Uses for Low-Carbon Cast Steel:

Low-carbon steel castings ordinarily are used in the annealed condition. Such steel has given good service when used for annealing boxes, ladles and other heavy articles subjected to high temperatures. Low-carbon steel castings are often case carburized for use as gears and other wear-resistant articles that require surface hardness combined with a tough and ductile core. The magnetic properties of this steel make it useful in the manufacture of electrical equipment. Brackets, axle-housings and some automotive and railroad castings have been made from this steel, although the higher carbon grade is superior for most structural purposes. However, large tonnages of low-carbon steel castings have been used in the "as cast" condition either because annealing facilities were not available, or because their properties as such were fully consistent with their need.

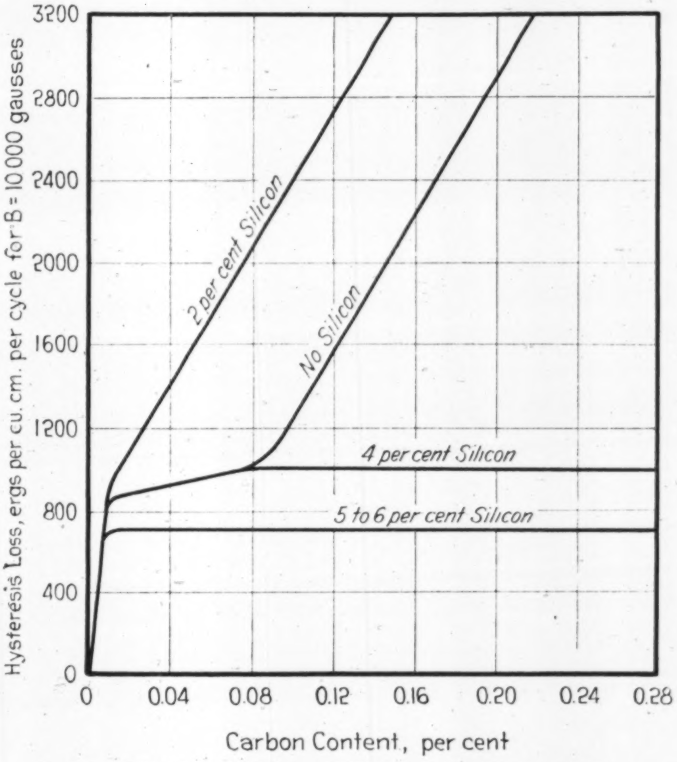

FIG. 2.—Effect of Carbon and Silicon on the Hysteresis Loss.

REGULAR-GRADE CARBON CAST STEEL

Properties at Room Temperature:

The regular-grade carbon-steel castings, ordinarily containing between 0.22 and 0.35 per cent carbon, represent the bulk of the steel

TABLE IV.—MECHANICAL PROPERTIES OF REGULAR GRADE OF CARBON CAST STEEL AT ROOM TEMPERATURE.

Steel	Chemical Composition, per cent					Mechanical Properties						Brinell Hardness Numbers	Treatment of Steel[a]	Investigators
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Impact Values			
No. 1....	0.23	0.66	0.21	0.03	0.05	62 000	....	34 000	13.0	....	....	....	1610° F. (875° C.), cooled in 36 hours	Giolitti (5)
						68 000	....	41 000	17.0	13.9	....	....	1520° F. (825° C.) (12), cooled in 10 hours	
						73 000	....	47 000	17.5	24.9	....	....	1610° F. (875° C.), slowly cooled; 1475° F. (800° C.) (20 minutes), hot water quenched, drawn (1), 1200° F. (650° C.)	
No. 2....	0.24	0.78	0.28	....	....	71 000	....	42 000	28.6	47.8	....	....	1650° F. (900° C.), furnace cooled	Hall, Nissen, Taylor (11)
No. 3....	0.25	0.68	0.32	0.032	0.012	67 000	27 000	....	22.0	33.0	20.1[b]	119	As received	Moore (15)
						77 000	44 000	....	30.5	51.0	32.6[b]	136	1650° F. (900° C.) (1), air cooled; 1525° F. (830° C. (1), air cooled	
						77 000	43 000	....	31.5	52.0	32.0[b]	136	1650° F. (900° C.) (1), air cooled; 1525° F. (830° C.) (1), air cooled; 600° F. (315° C.) (1), air cooled	
						76 000	43 000	....	31.7	56.0	34.0[b]	133	1650° F. (900° C.) (1), air cooled; 1525° F. (830° C.) (1), air cooled; 1000° F. (540° C.) (1), air cooled	
No. 4....	0.25	0.44	0.29	0.07	0.105	56 000	....	....	5.2	4.5	1.4[c]	....	As cast (bessemer cast steel)	Körber, Pomp (16)
						64 000	....	....	15.9	16.5	1.1[c]	....	Annealed, slowly cooled	
						70 000	....	....	8.3	12.8	2.9[c]	....	Annealed, rapidly cooled	
No. 5....	0.25	0.71	0.13	0.030	0.021	56 000	....	....	22.6	37.3	2.1[c]	....	As cast (basic open hearth)	
						68 000	....	....	27.8	51.3	2.0[c]	....	Annealed, slowly cooled	
						74 000	....	....	20.3	30.3	8.5[c]	....	Annealed, rapidly cooled	
No. 6....	0.26	0.84	0.37	....	....	75 000	....	....	33.0	54.2	....	....	Annealed, furnace cooled	Melmoth (9)
No. 7....	0.27	0.71	0.41	....	....	72 000	....	46 000	32.9	57.6	35.5[d]	....	1650° F. (900° C.), water quenched; 1300° F. (705° C.), furnace cooled	Hall, Nissen, Taylor (11)
No. 8....	0.28	0.74	0.37	0.028	0.036	75 000	36 000	33 000	18.3	28.3	1.5[c]	....	1690° F. (920° C.), furnace cooled	Körber, Pomp (8)
No. 9....	0.28	0.65	0.27	0.032	0.027	74 000	43 000	....	28.0	42.0	....	....	1550° F. (840° C.) (7), furnace cooled to 1000° F. (540° C.), air cooled	Bull (18)

[a] Numbers in parentheses correspond to number of hours at temperature.
[b] Charpy, ft-lb.
[c] Specimen 30 by 30 by 160 mm. Cylindrical notch 4 mm. in diameter, 15 mm. deep. Values in m-kg. per sq. cm.
[d] Frémont, kg-m.

TABLE IV.—*Continued.*

Steel	Chemical Composition, per cent					Mechanical Properties						Brinell Hardness Numbers	Treatment of Steel[a]	Investigators
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Impact Values			
No. 10...	0.30	0.79	0.33	0.026	0.030	75 000	36 000	....	19.5	29.0	17[e]	156	As cast	Mitchell (20)
						76 000	42 000	....	25.5	31.5	21[e]	143	Annealed	
						84 000	57 000	....	44.0	65.0	44[e]	160	1650° F. (900° C.), water quenched, drawn 1300° F. (705° C.), air cooled	
						95 000	68 000	....	24.0	57.0	....	192	1650° F. (900° C.), water quenched, drawn 1100° F. (595° C.), air cooled	
						108 000	79 000	....	19.0	46.0	....	220	1650° F. (900° C.), water quenched, drawn 900° F. (480° C.), air cooled	
						119 000	90 000	....	14.0	33.0	....	238	1650° F. (900° C.), water quenched, drawn 700° F. (370° C.), air cooled	
						130 000	100 000	....	9.0	18.0	....	250	1650° F. (900° C.), water quenched, drawn 500° F. (260° C.), air cooled	
No. 11...	0.30	0.62	0.181	0.038	0.038	87 000	57 000	....	15.3	22.8	14.25[b]	176	1650° F. (900° C.) (2), water quenched, drawn 1200° F. (650° C.), furnace cooled	Langenberg (21)
						79 000	46 000	....	18.3	27.2	11.32[b]	156	1650° F. (900° C.) (2), furnace cooled	
						83 000	50 000	....	16.2	23.9	11.87[b]	159	1740° F. (950° C.) (2), air cooled, drawn 930° F. (500° C.) (2), furnace cooled	
No. 12...	0.31	0.94	0.31	....	....	78 000	....	48 000	26.2	41.3	....	....	1650° F. (900° C.), furnace cooled	Hall, Nissen, Taylor (11)
No. 13...	0.33	0.77	0.34	....	....	83 000	4 000	....	25.0	38.5	....	....	....	Spring (23)
No. 14...	0.34	0.84	0.39	0.09	0.031	85 000	....	....	10.0	10.0	1.1[c]	....	As cast	Körber, Pomp (16)
						79 000	40 000	....	18.9	24.7	3.3[c]	....	Annealed, slowly cooled	
						86 000	54 000	....	14.3	19.3	4.8[c]	....	Annealed, rapidly cooled	
No. 15...	0.34	0.96	0.19	0.02	0.06	87 000	....	51 000	18.0	21.0	1.7[c]	....	As cast	Giolitti (5)
						86 000	....	55 000	25.0	33.5	6.15[c]	....	1560° F. (850° C.) (3), slowly cooled	
						91 000	....	63 000	24.0	40.5	7.41[c]	....	1560° F. (850° C.), air cooled, drawn 1020° F. (550° C.)	
						89 000	....	59 000	30.0	53.0	11.75[c]	....	Forged, 1560° F. (850° C.) (3), slowly cooled	
No. 16...	0.34	0.86	0.61	....	....	88 000	....	55 000	24.3	35.6	32.5[d]	....	As received (treatment not known)	Hall, Nissen, Taylor (11)
						83 000	....	55 000	21.0	32.7	30.0[d]	....	1650° F. (850° C.) (4), water quenched, drawn 1250° F. (675° C.) (6), air cooled	
						97 000	....	58 000	22.2	31.4	12.5[d]	....	1650° F. (850° C.) (4), air cooled, drawn 1290° F. (700° C.) (6), air cooled	

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[a] Numbers in parentheses correspond to number of hours at temperature.

[b] Charpy, ft-lb.

[c] Specimen 30 by 30 by 160 mm. Cylindrical notch 4 mm. in diameter, 15 mm. deep. Values in m-kg. per sq. cm.

[d] Frémont, kg-m.

[e] Izod, ft-lb.

foundry output. Their mechanical properties are chiefly determined as the result of the amount of carbon they contain.

The mechanical properties at room temperature of a large number of steels are tabulated in Table IV. These results have been gathered from many sources and have been arranged in the order of increasing carbon contents.

These steels are decidedly susceptible to regular methods of heat treatment. A few investigators(5,19) have shown that ordinary heating of the castings to above the critical point and cooling slowly is of relatively little benefit, and that furnace cooling or slow cooling is decidedly inferior to air cooling for development of maximum strength in this grade of cast steel. To develop mechanical properties to the fullest degree the castings should be heat treated by quenching and drawing, if the design presents no obstacle, in the judgment of the experienced founder. After such treatment the regular-grade steel castings often have properties equal or superior to many of the annealed alloy steel castings. The quenched-and-drawn specimens of steels Nos. 1, 10 and 11 are excellent examples of the improvement in properties brought about through heat treating. Mitchell(20) believes that there is no limit to the size or type of casting that can be liquid quenched, except as the size is limited by the furnace equipment. Mann(19) reports that, with a suitable homogeneity heat treatment followed by quenching in oil, regular-grade steel castings were developed with structures and properties that correspond to the best forged steel.

TABLE V.—ENDURANCE PROPERTIES OF REGULAR-GRADE CAST STEEL.

Steel	Carbon Content, per cent	Endurance Properties			Treatment of Steel[a]
		Tensile Strength, lb. per sq. in.	Endurance Limit, lb. per sq. in.	Endurance Ratio	
No. 3......	0.25	67 000	27 000	0.40	As received.
		77 000	35 000	0.46	1650° F. (900° C.) (1), air cooled; 1525° F. (830° C.) (1), air cooled.
		77 000	31 000	0.40	1650° F. (900° C.) (1), air cooled; 1525° F. (830° C.) (1), air cooled; 600° F. (315° C.) (1), air cooled.
		76 000	33 000	0.43	1650° F. (900° C.) (1), air cooled; 1525° F. (830° C.) (1), air cooled; 1000° F. (540° C.) (1), air cooled.
No. 10*a*....	0.30	74 000	....	0.40	As cast.
		75 000	....	0.44	Annealed.
		84 000	....	0.50	1650° F. (900° C.), water quenched. Drawn 1300° F. (705° C.).

[a] Nnmbers in parentheses correspond to number of hours at temperature.

For years Giolitti(5) has stressed the need for a homogeneity heat treatment to overcome ingotism in castings of large section. The phenomena of intercrystalline liquation and segregation are difficult to overcome, unless the casting is held for a long time at a temperature considerably above the upper critical. Many of the failures of steel castings to respond to a full anneal or a normalizing treatment can be traced directly to ingotism or heterogeneity of structure, which at the temperature of the treatment is removed very slowly. For this reason a double treatment is sometimes resorted to, the first to bring homogeneity and the second to control the grain structure. Under favorable casting conditions and by the use of suitable heat treatment, cast steel can be produced having static and dynamic properties that are equal to or but slightly less than the properties of rolled and forged steel of similar chemical composition.

Endurance Properties of Regular-Grade Cast Steel.—Moore(15) has determined the endurance properties of steel No. 3, Table IV, following various normalizing treatments. The results are given in Table V.

Although the endurance ratio for cast steel in the "as cast" condition is slightly less than the average for ordinary rolled steel, it is raised on normalizing and becomes equal to that of rolled steel when water quenched and drawn. The results given for steel No. 10*a*(20) are the average of several tests; consequently, the increase in endurance ratio resulting from heat treatment is quite convincing.

Magnetic Properties of Regular-Grade Carbon Cast Steel.—Cast steel used for electrical machines differs in composition very little from ordinary cast steel. Schmid(25) has given the composition of cast steel used wherever the material requires dynamic or magnetic properties as follows: carbon 0.12 to 0.30 per cent, silicon 0.25 to 0.45 per cent, manganese 0.45 to 0.85 per cent, and phosphorus and sulfur, each less than 0.05 per cent. The lower carbon steel with a minimum tensile strength of 54,000 lb. per sq. in. and 20 per cent elongation is used for stationary parts of motors. A higher carbon steel with a minimum tensile strength of 64,000 lb. per sq. in. and 16 per cent elongation is used for rotating parts. The elongation of only 16 per cent is quite unusual for steel made in America.

Cast steel of high magnetic induction differs very little in composition from ordinary cast steel. The total amount of carbon, manganese, sulfur and phosphorus is kept somewhat lower, and the strength values are obtained through an increase in silicon content. A cast steel known in Germany as D. I. Norm. 1681 is of special quality and high magnetic induction(26), values for the latter being as follows: 14,500 c.g.s. units for a field strength of 25 Aw. per cm.; 16,000 c.g.s. units at 50 Aw. per cm.; and 17,500 c.g.s. units at 100 Aw. per cm.

TABLE VI.—PROPERTIES OF REGULAR-GRADE CARBON CAST STEEL AT ELEVATED TEMPERATURES.

Steel	Chemical Composition, per cent					Mechanical Properties	Temperature of Test									
	Carbon	Manganese	Silicon	Sulfur	Phosphorus		70° F. (21° C.)	125° F. (50° C.)	212° F. (100° C.)	300° F. (150° C.)	390° F. (200° C.)	480° F. (250° C.)	570° F. (300° C.)	660° F. (350° C.)	750° F. (400° C.)	930° F. (500° C.)
No. 4 As cast.	0.25	0.44	0.29	0.07	0.105	Tensile strength, lb. per sq. in.	56 000	....	56 000	....	67 000	....	71 000	....	63 000	....
						Yield point, lb. per sq. in.	....	....	....	....	....	....	....	....	....	....
						Elongation, per cent	5.2	....	10.2	....	7.0	....	8.1	....	16.7	....
						Reduction of area, per cent	4.5	....	16.0	....	14.5	....	13.5	....	25.0	....
						Impact, m-kg. per sq. cm	1.4	1.8	2.9	6.3	6.3	7.1	6.7	6.0	5.6	4.2
No. 4 Annealed, slowly cooled.	0.25	0.44	0.29	0.07	0.105	Tensile strength, lb. per sq. in.	64 000	....	57 000	....	64 000	....	62 000	....	62 000	....
						Yield point, lb. per sq. in.	29 000	....	....	....	....	....	....	....	....	....
						Elongation, per cent	15.9	....	14.0	....	8.0	....	7.8	....	20.0	....
						Reduction of area, per cent	16.5	....	22.0	....	15.7	....	16.0	....	25.5	....
						Impact, m-kg. per sq. cm	1.1	1.4	2.4	6.2	9.2	9.2	10.2	8.5	8.0	6.1
No. 4 Annealed, rapidly cooled.	0.25	0.44	0.29	0.07	0.105	Tensile strength, lb. per sq. in.	70 000	....	70 000	....	84 000	....	80 000	....	69 000	....
						Yield point, lb. per sq. in.	43 000	....	43 000	....	41 000	....	39 000	....	....	....
						Elongation, per cent	8.3	....	10.5	....	6.7	....	8.5	....	9.2	....
						Reduction of area, per cent	12.8	....	22.7	....	15.0	....	13.3	....	15.0	....
						Impact, m-kg. per sq. cm	2.9	4.2	9.3	8.3	10.2	8.2	7.2	6.3	5.2	4.2
No. 5 As cast.	0.25	0.71	0.13	0.030	0.021	Tensile strength, lb. per sq. in.	56 000	....	54 000	....	65 000	....	60 000	....	58 000	....
						Yield point, lb. per sq. in.	....	....	....	....	....	....	....	....	....	....
						Elongation, per cent	22.6	....	13.0	....	11.2	....	9.6	....	17.0	....
						Reduction of area, per cent	37.3	....	33.0	....	20.0	....	16.4	....	24.0	....
						Impact, m-kg. per sq. cm	2.1	3.0	6.1	9.7	11.9	11.4	10.0	9.1	8.3	6.6
No. 5 Annealed, slowly cooled.	0.25	0.71	0.13	0.030	0.021	Tensile strength, lb. per sq. in.	68 000	....	55 000	....	63 000	....	63 000	....	59 000	....
						Yield point, lb. per sq. in.	36 000	....	31 000	....	30 000	....	....	....	....	....
						Elongation, per cent	27.8	....	14.6	....	9.0	....	8.7	....	10.3	....
						Reduction of area, per cent	51.3	....	24.5	....	16.5	....	15.3	....	15.5	....
						Impact, m-kg. per sq. cm	2.0	6.7	10.9	11.8	11.9	11.8	11.3	10.1	7.7	6.5
No. 5 Annealed, rapidly cooled.	0.25	0.71	0.13	0.030	0.021	Tensile strength, lb. per sq. in.	75 000	....	69 000	....	78 000	....	80 000	....	67 000	....
						Yield point, lb. per sq. in.	43 000	....	42 000	....	41 000	....	....	....	....	....
						Elongation, per cent	20.3	....	25.1	....	13.1	....	15.9	....	25.2	....
						Reduction of area, per cent	30.3	....	51.3	....	26.0	....	20.7	....	35.5	....
						Impact, m-kg. per sq. cm	8.5	13.1	15.9	14.0	12.6	12.0	11.0	9.4	7.0	5.8
No. 5a 1670° F. (910° C.) (5), cooled in furnace.	0.26	0.85	0.38	0.012	0.016	Tensile strength, lb. per sq. in.	77 000	....	70 000	....	67 000	....	71 000	....	65 000	47 000
						Yield point, lb. per sq. in.	38 000	....	35 000	....	32 000	....	27 000	....	25 000	23 000
						Elastic limit, lb. per sq. in.	38 000	....	35 000	....	32 000	....	23 000	....	17 000	15 000
						Elongation, per cent	23.4	....	25.4	....	21.9	....	19.3	....	25.6	32.7
						Reduction of area, per cent	41.1	....	41.6	....	39.6	....	29.5	....	47.5	69.2
						Impact, m-kg. per sq. cm	7.7	....	14.2	....	14.4	....	14.4	....	13.1	9.3

TABLE VI.—*Continued.*

Steel	Chemical Composition, per cent					Mechanical Properties	Temperature of Test									
	Carbon	Manganese	Silicon	Sulfur	Phosphorus		70° F. (21° C.)	125° F. (50° C.)	212° F. (100° C.)	300° F. (150° C.)	390° F. (200° C.)	480° F. (250° C.)	570° F. (300° C.)	660° F. (350° C.)	750° F. (400° C.)	930° F. (500° C.)
No. 8 1690° F. (920° C.) (8), furnace cooled.	0.28	0.74	0.37	0.028	0.036	Tensile strength, lb. per sq. in.	75 000	....	66 000	....	64 000	....	71 000	....	64 000	45 000
						Yield point, lb. per sq. in.	36 000	....	31 000	....	30 000	....	29 000	....	27 000	24 000
						Elastic limit, lb. per sq. in.	33 000	....	29 000	....	28 000	....	22 000	....	17 000	11 000
						Elongation, per cent	18.3	....	18.3	....	7.8	....	11.9	....	9.8	21.2
						Reduction of area, per cent	28.3	....	31.6	....	16.0	....	15.6	....	16.1	28.9
						Impact, m-kg. per sq. cm	1.5	....	8.6	....	12.2	....	12.3	....	9.0	6.6
No. 9 1550° F. (840° C.) (7), cooled in furnace to 1000° F. (540° C.), air cooled.	0.28	0.65	0.27	0.032	0.027	Tensile strength, lb. per sq. in.	74 000	74 000	74 000	75 000	79 000	85 000	84 000	77 000	65 000	45 000
						Yield point, lb. per sq. in.	43 000	43 000	38 000	38 000	38 000	38 000	31 000	32 000	33 000	22 000
						Elongation, per cent	28.0	26.0	22.0	20.0	18.0	15.0	19.0	22.0	25.0	30.0
						Reduction of area, per cent	42.0	40.0	38.0	34.0	29.0	28.0	24.0	29.0	40.0	46.0
No. 9*a* 1550° F. (840° C.) (7), cooled in furnace to 1000° F., air cooled.	0.30	0.67	0.38	0.020	0.027	Tensile strength, lb. per sq. in.	78 000	77 000	73 000	72 000	74 000	75 000	78 000	73 000	65 000	43 000
						Yield point, lb. per sq. in.	43 000	42 000	40 000	37 000	33 000	29 000	26 000	25 000	24 000	21 000
						Elongation, per cent	30.0	29.0	27.0	25.0	23.0	19.0	21.0	27.0	33.0	41.0
						Reduction of area, per cent	34.0	34.0	34.5	35.0	37.0	24.0	30.0	33.0	42.0	51.0
No. 21 As cast.	0.33	0.88	0.36	0.030	0.043	Tensile strength, lb. per sq. in.	80 000	....	74 000	....	75 000	....	75 000	....	75 000	58 000
						Elastic limit, lb. per sq. in.	40 000	....	38 000	....	38 000	....	37 000	....	35 000	33 000
						Elongation, per cent	11.0	....	13.0	....	11.0	....	9.8	....	13.0	12.5
						Reduction of area, per cent	18.0	....	26.0	....	21.0	....	17.0	....	31.0	38.0
No. 21 1600° F. (870° C.) (4), air cooled to 1100° F. (595° C.), furnace cooled.	0.33	0.88	0.36	0.030	0.043	Tensile strength, lb. per sq. in.	83 000	....	82 000	....	80 000	....	81 000	....	80 000	55 000
						Elastic limit, lb. per sq. in.	49 000	....	48 000	....	34 000	....	37 000	....	33 000	....
						Elongation, per cent	16.0	....	16.5	....	16.5	....	13.0	....	14.5	25.0
						Reduction of area, per cent	33.0	....	34.0	....	33.0	....	24.0	....	29.0	53.0
No. 23 As cast.	0.34	0.84	0.39	0.09	0.031	Tensile strength, lb. per sq. in.	85 000	....	79 000	....	81 000	....	81 000	....	72 000	....
						Yield point, lb. per sq. in.	....	....	....	....	....	....	....	....	....	....
						Elongation, per cent	10.0	....	11.1	....	6.4	....	6.8	....	7.3	....
						Reduction of area, per cent	10.0	....	16.0	....	12.0	....	11.0	....	12.0	....
						Impact, m-kg. per sq. cm	1.1	1.3	2.2	3.7	5.8	7.1	7.0	6.9	6.5	4.6
No. 23 Annealed, slowly cooled.	0.34	0.84	0.39	0.09	0.031	Tensile strength, lb. per sq. in.	79 000	....	72 000	....	62 000	....	65 000	....	65 000	....
						Yield point, lb. per sq. in.	40 000	....	37 000	....	33 000	....	....	....	....	....
						Elongation, per cent	18.9	....	21.6	....	21.5	....	8.0	....	18.9	....
						Reduction of area, per cent	24.7	....	29.0	....	40.5	....	11.7	....	30	....
						Impact, m-kg. per sq. cm	3.3	5.0	8.4	10.3	9.6	11.1	9.9	10.7	7.8	6.5
No. 23 Annealed, rapidly cooled.	0.34	0.84	0.39	0.09	0.031	Tensile strength, lb. per sq. in.	87 000	....	83 000	....	97 000	....	96 000	....	81 000	....
						Yield point, lb. per sq. in.	54 000	....	50 000	....	50 000	....	....	....	....	....
						Elongation, per cent	14.3	....	13.4	....	10.3	....	12.5	....	14.7	....
						Reduction of area, per cent	19.3	....	21.0	....	17.0	....	17.5	....	25.0	....
						Impact, m-kg. per sq. cm	4.8	9.2	13.4	12.9	12.2	11.8	11.1	9.1	6.9	5.9

Physical Properties of Regular-Grade Carbon Steel Castings at Low and Elevated Temperatures:

Some of the results of investigations of the properties of the regular-grade cast steels at elevated temperatures are recorded in Table VI. At increasing temperatures the tensile strength of this grade of cast steel increases until it reaches a maximum at 400 to 600° F. (205 to 315° C.). Corresponding to this change, the elastic limit and yield point continuously decrease, while the reduction of area and elongation become a minimum in the same temperature range. The variations in mechanical properties with temperature are well brought out in Table VI and are particularly well demonstrated in Fig. 3, which is a reproduction of data by R. J. Doty, and quoted by Bull(18). Heat A is steel No. 9 in Table IV.

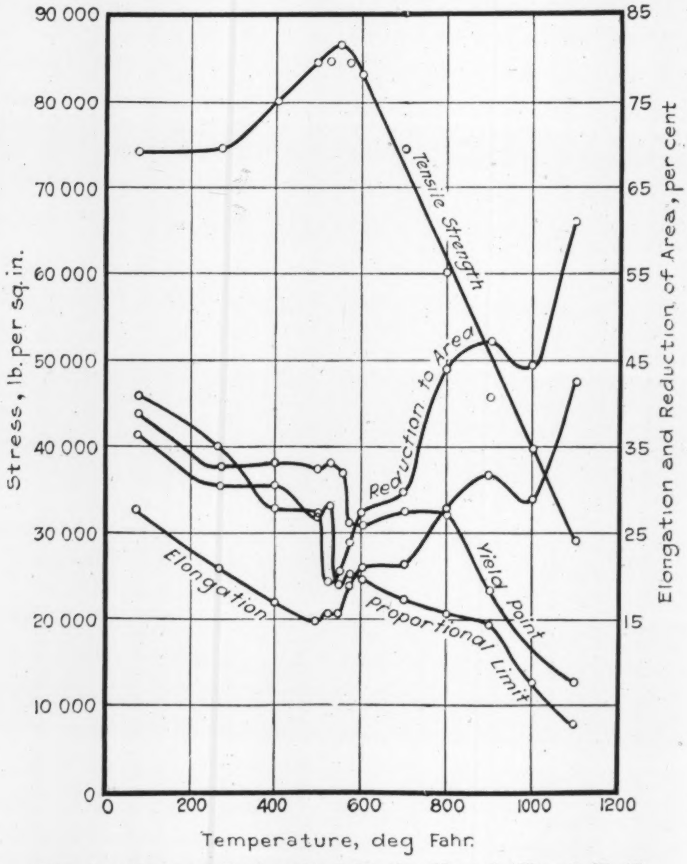

FIG. 3.—Tests on Carbon Cast Steel. Heat A (Doty) (Bull).

The blue brittle range in impact is regularly found at higher temperatures and in this respect some of the steels show low values of impact at 700 to 750° F. (370 to 400° C.).

Properties of Regular-Grade Carbon Steel Castings at Low Temperatures:

Relatively few tests have been made on cast steels exposed to low temperatures. Bull(18) cites tests made by H. B. Bowen at room temperature and at −114° F. (−81° C.) on a cast steel containing 0.21 per cent carbon, 0.70 per cent manganese, 0.030 per cent sulfur, and 0.010 per cent phosphorus. At the above-mentioned temperatures, the steel had the following properties:

CONDITION OF TEST	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT	IZOD IMPACT, FT-LB.
Room temperature..	72 000	37 000	34.75	55.32	36.0
−114° F. (−81° C.).	78 000	40 000	33.25	52.52	3.0

The small decrease in elongation and reduction of area indicates a slight embrittlement at low temperatures, whereas the large decrease in Izod impact value indicates a very large degree of embrittlement. This difference in effects, the comparison between the impact values, and the changes in elongation and reduction of area for steels at temperatures in the blue brittleness range indicate that these two methods do not express the same degree of ductility in metals, but that each method of totally dissimilar rates of testing is variously sensitive at different temperatures.

Moffatt(27) determined the impact resistance at low temperatures of a plain carbon steel casting containing 0.23 per cent carbon, 0.66 per cent manganese, 0.23 per cent silicon, 0.046 per cent sulfur and 0.029 per cent phosphorus. The results, taken from a series of curves, are as follows:

	IZOD IMPACT, FT-LB. PER SQ. IN.					
CONDITION OF MATERIAL	60° F. (15° C.)	40° F. (4° C.)	20° F. (−6° C.)	0° F. (−18° C.)	−20° F. (−29° C.)	−40° F. (−40° C.)
As cast..........................	130	105	80	55	40	...
Heated to 1600° F. (870° C.), furnace cooled to 1100° F. (595° C.), air cooled..........................	235	210	185	165	150	135
Heated to 1600° F. (870° C.), water quenched. Heated to 1450° F. (790° C.), furnace cooled to 1100° F. (595° C.), air cooled..............	330	305	275	245	220	195

There is a constant drop in the impact resistance as the temperature is lowered. The impact resistance of some forged and rolled carbon steels, whose compositions are sufficiently close to those of cast steel, have been determined at both low and elevated temperatures. The results of a few investigations (28,29,18) are tabulated in Table VII.

TABLE VII.—IMPACT RESULTS ON WROUGHT STEEL.

Langenberg			Körber and Pomp					Bull					
								Morrison and Cameron Results					
Temperature		Charpy Impact, ft-lb., Average[a]	Temperature		Impact, m-kg. per sq. cm.[b]			Temperature		Charpy Impact, ft-lb.[c]	Temperature		Charpy Impact, ft-lb.[c]
deg. Fahr.	deg. Cent.		deg. Fahr.	deg. Cent.	Rolled	Over-heated	Quenched and Drawn	deg. Fahr.	deg. Cent.		deg. Fahr.	deg. Cent.	
−80	−62	18.63	−94	−70	1.1	0.5	1.3	Quenched at 1575° F. (885° C.)			Quenched at 1575° F. (855° C.). Drawn at 1165° F. (635° C.).		
−60	−51	18.25	−40	−40	8.4	1.1	12.5						
−40	−40	15.42	−4	−20	9.4	1.4	14.2						
−20	−29	21.21	32	0	10.9	6.6	14.2						
0	−18	13.13	68	20	11.2	7.2	17.3	−25	−32	15.0	−26	−32	31.0
15	−9	18.56	122	50	12.3	8.9	17.0	−18	−28	12.0	−18	−28	26.0
32	0	16.39	212	100	12.4	10.5	16.9	−10	−23	8.0	−10	−23	27.0
50	10	29.05	302	150	11.8	11.1	17.1	−4	−20	10.5	−4	−20	26.5
70	21	31.19	392	200	11.5	11.1	16.2	12	−11	11.0	12	−11	31.5
90	32	43.20	482	250	10.0	9.5	15.4	68	20	26.5	68	20	42.0
110	43	39.78	572	300	9.1	8.1	13.6						
130	54	167.20	662	350	6.9	6.8	11.3	Quenched at 1575° F. (855° C.). Drawn at 440° F. (225° C.)			Normalized at 1575° F. (855° C.)		
150	65	187.76	752	400	6.5	6.2	8.1						
175	80	229.64	932	500	5.0	5.1	5.8						
200	93	293.05											
225	105	310.24						−25	−32	9.5	−24	−31	9.0
250	120	338.86						−18	−28	9.5	−18	−28	8.0
350	175	400.89						−10	−23	14.0	−10	−23	17.5
500	260	387.87						−4	−20	12.5	−3	−19	18.0
750	400	313.20						12	−11	14.0	12	−11	20.7
1000	540	195.09						68	20	16.5	68	20	29.0
								Quenched at 1575° F. (855° C.). Drawn at 810° F. (430° C.)					
								−26	−32	21.0			
								−18	−28	21.5			
								−10	−23	22.0			
								−4	−20	24.0			
								12	−11	25.5			
								68	20	30.0			

[a] Specimen: 6.102 by 1.181 by 1.181 in. Treatment: 1652° F. (900° C.) (1½ hours), furnace cooled. Composition: Carbon, 0.36; manganese, 0.40; silicon, 0.26; sulfur, 0.044; phosphorus, 0.054 per cent.

[b] Composition: Carbon, 0.23; manganese, 0.73; silicon, 0.02; sulfur, 0.028; phosphorus, 0.40 per cent.

[c] Composition: Carbon, 0.34; manganese, 0.60; sulfur, 0.042; phosphorus, 0.014 per cent.

It appears from these data on impact properties at low temperatures that the ductility of the steel sharply changes in a narrow range of temperatures close to 32° F. (0° C.); also that the type of heat treatment given the steel has a decided influence on the temperature at which embrittlement occurs. A quench-and-draw treatment shifts the appearance of the embrittlement to somewhat lower temperatures.

CREEP STRESS IN PLAIN CARBON STEELS

Spring(23) and Kanter and Spring(30) have made outstanding contributions to the industry by their flow or creep tests on cast steels. Their results indicate that cast steel will withstand a somewhat higher temperature without deformation at the same load than will rolled or forged steel of similar composition. Their proposed explanation of this is that above the so-called equicohesive temperature, that is, the temperature above which strain-hardening ceases, it appears that slip once started by rolling or forging is continued with less stress than was required to start it initially.

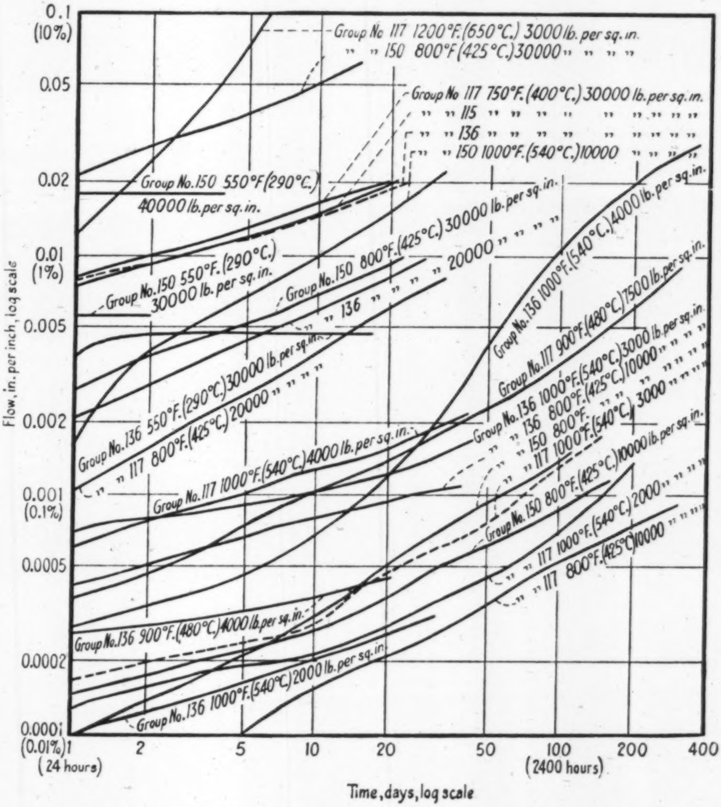

FIG. 4.—Flow-Time Curves for Annealed Carbon Cast Steel. (Kanter and Spring.)

More recent work of the National Physical Laboratory(31) on one steel shows exactly opposite results to those of Kanter and Spring. At 932° F. (500° C.) the comparative tension and creep test values for a forged steel with 0.25 per cent carbon, a cast steel with 0.30

per cent carbon, and another forged steel with 0.40 per cent carbon are given as follows:

	MAXIMUM STRESS, TENSION TEST, LB. PER SQ. IN.		CREEP STRESS FOR MINIMUM STRAIN RATE OF 0.00001 IN. PER INCH PER HOUR, LB. PER SQ. FT.	
TYPE OF STEEL	AS RECEIVED	AFTER 2000 HOURS AT 1040° F. (560° C.)	AS RECEIVED	AFTER 2000 HOURS AT 1040° F. (560° C.)
0.25 per cent carbon, forged....	33 000	.....	11 500	.....
0.30 per cent carbon, cast	34 000	27 500	11 200	9 200
0.40 per cent carbon, forged....	51 500	40 000	17 250	13 200

The tensile stresses were the maximum ones developed when the specimens were tested with a straining rate of 0.001 in. per inch per minute, while the creep stresses were the values giving a minimum creep rate of 0.00001 in. per inch per hour.

On the assumption that the compositions of the steels were not materially different except in their carbon contents, the results indicate a slightly superior resistance to constant deformation for the forged specimens. It was recognized by the investigators, however, that a coarse structure, which ordinarily is undesirable in a steel for use at low temperatures, is more than likely to be associated with a greater resistance to deformation at elevated temperatures than is a fine structure.

These investigators emphasize the fact that definite reductions in the creep resistance of carbon steels occur when the pearlite constituent is changed from the lamellar to the spheroidized form. It becomes increasingly difficult to spheroidize steel if the structure is coarse, as in cast steel. Thus, the contentions of Kanter and Spring are supported.

In presenting creep test data we have made no distinction between classes of carbon-steel castings, as most of the tests cover the regular grade of cast steel.

Figure 4 shows flow-time curves for annealed cast steel plotted to logarithmic scale, taken from the results given by Kanter and Spring(32). Many of the curves take the form of straight or nearly straight lines and may afford a convenient device for estimating long-time creep values from tests of only a few hundred hours' duration.

The compositions of the steels appearing in Fig. 4 and designated as groups Nos. 117, 136, and 150 are as follows:

GROUP	CARBON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT	SULFUR, PER CENT	PHOSPHORUS, PER CENT
No. 117.......	0.33	0.77	0.34	0.029	0.032
No. 136.......	0.40	0.70	0.32	0.015	0.022
No. 150.......	0.20	0.60	0.24	0.033	0.032

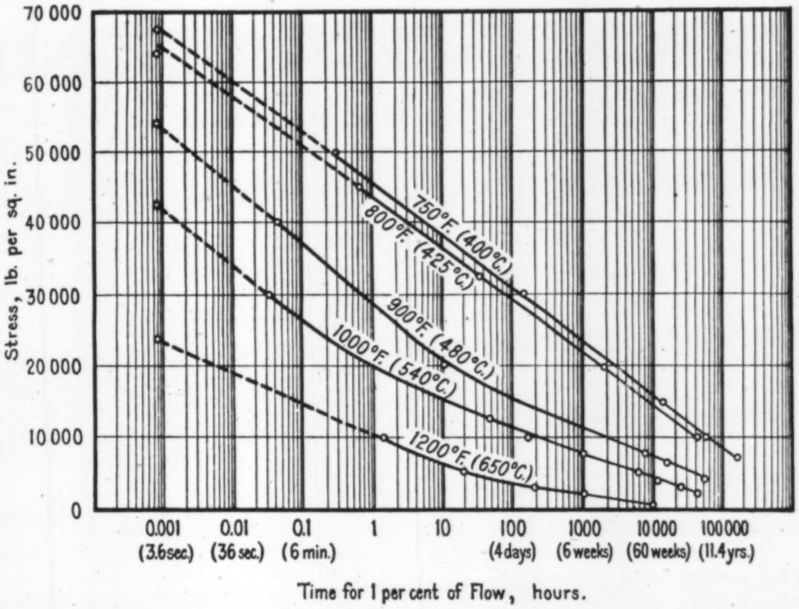

FIG. 5.—Relationship Between Load and Time to Produce 1 per cent of Flow in Annealed Carbon Cast Steel at Different Temperatures. (Spring.)

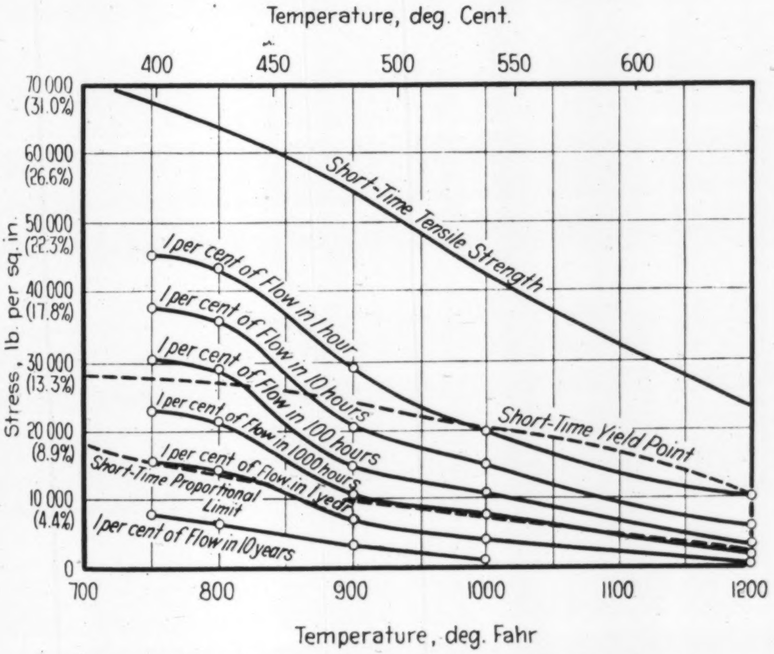

FIG. 6.—Iso Flow Rate Curves for Carbon Cast Steel. (Spring.)

Figures 5 and 6, taken from the work of Spring(23), lead to interesting interpretations of creep data. In Fig. 5 is plotted logarithmically stress in pounds per square inch against time in hours for 1 per cent flow. When the short-time tensile strengths are plotted against the time ordinate for 1 per cent of flow at a pulling speed of 3 seconds and are then connected to the load-time graphs, the curves appear continuous. This seems to indicate a relationship between the applied stress, the short-time test, and the long-time flow or creep test.

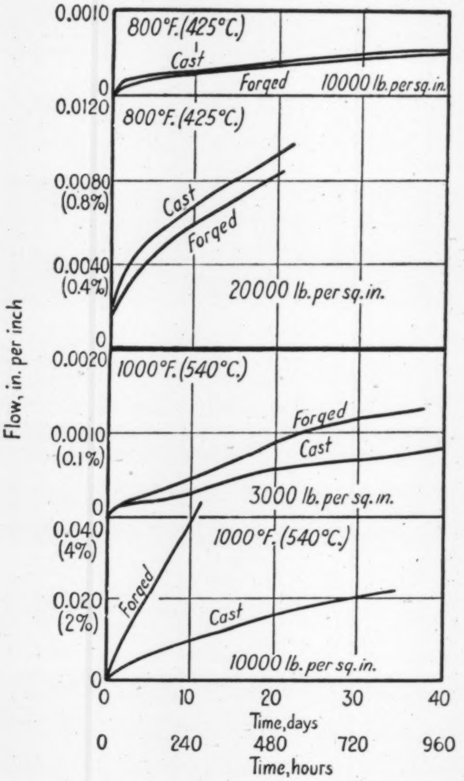

FIG. 7.—Flow-Time Curves for 0.20 per cent Carbon Steel.

Comparison of annealed cast steel with annealed forged steel of identical analysis.

The same information is plotted somewhat differently in Fig. 6. The curves for the two figures were obtained from tests on a steel corresponding in composition to group No. 117. They are useful in determining at once the rate of flow for a given temperature and stress.

Spring(23) has compared the creep stresses of steels in the cast and the forged and rolled condition. He has found that the wrought material, at a given load, creeps more rapidly than the cast material, especially at temperatures in the vicinity of 1000° F. (540° C.). To throw further light on the subject, forged and cast bars of identical analysis were tested in both long-time and short-time tests. Flow-time charts of the test are summarized in Figs. 7, 8 and 9. At 800° F. (425° C.) and 10,000 lb. per sq. in. stress (Fig. 7) the curves for the two materials are identical. At 1000° F. (540° C.), especially for a stress of 10,000 lb. per sq. in., the cast material shows to advantage, since its resistance to creep is more than four times that of the wrought material.

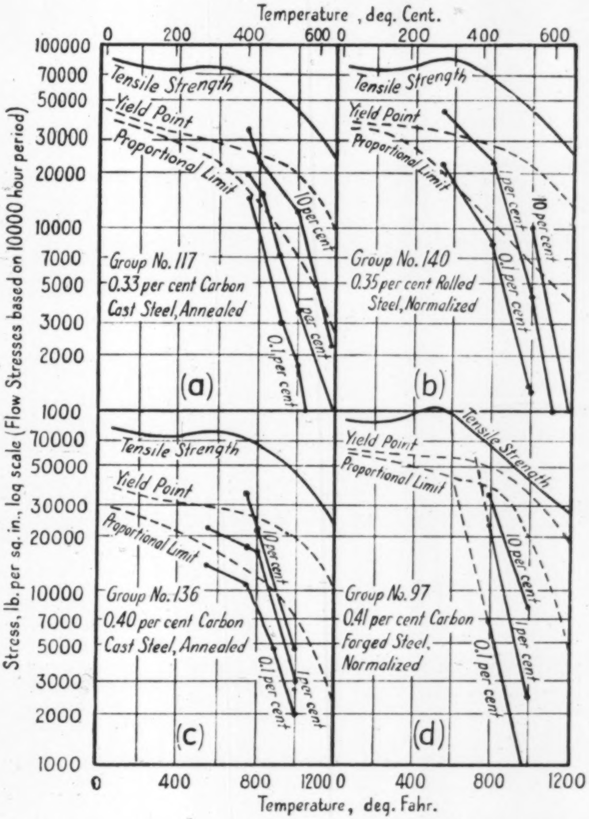

FIG. 8.—Stress-Temperature Curves for Long-Time and Short-Time Tension Tests of Cast and Wrought Steels.

Figures 8 and 9 are stress-temperature curves for long-time and short-time tension tests of cast and wrought steels. The heavy

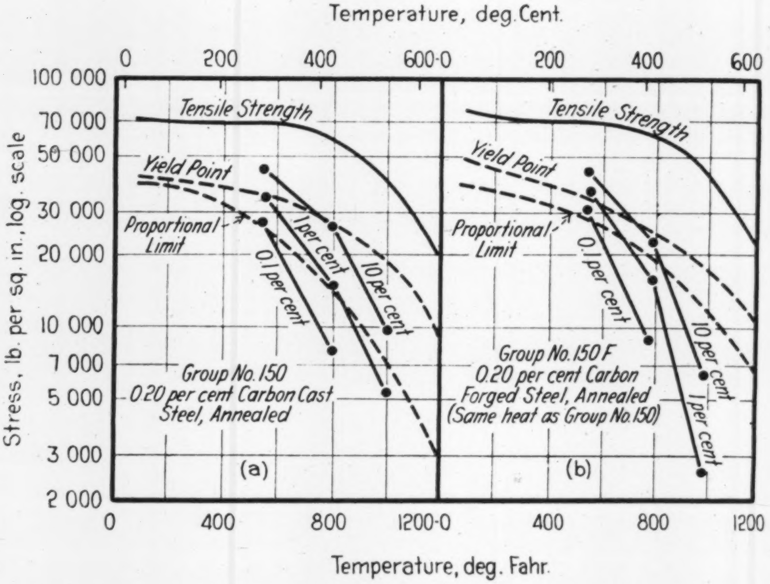

FIG. 9.—Stress-Temperature Curves for Long-Time and Short-Time Tension Tests of Cast and Wrought Steels.

Flow stress based on 10,000-hour period.

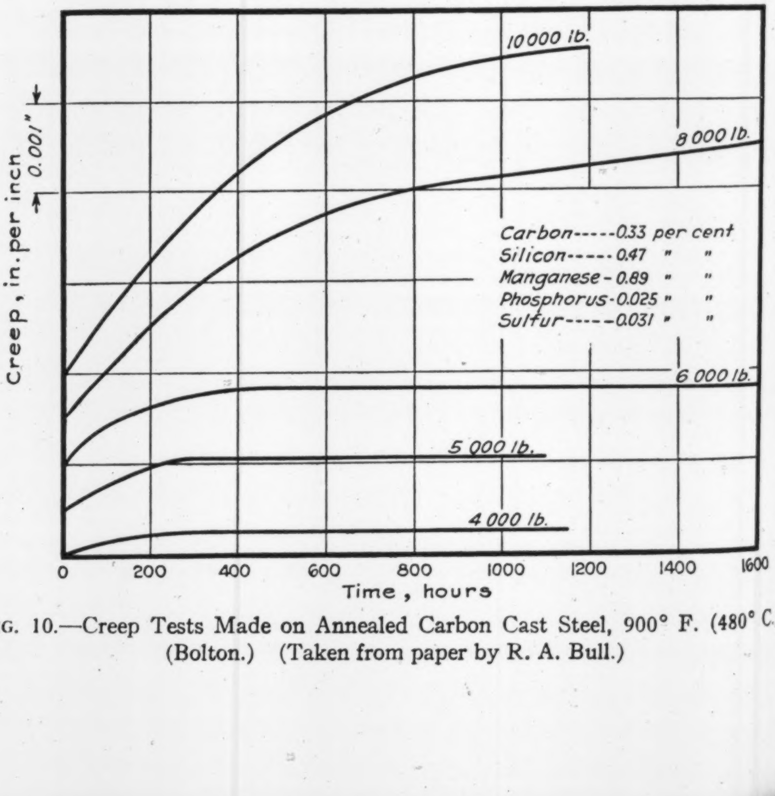

FIG. 10.—Creep Tests Made on Annealed Carbon Cast Steel, 900° F. (480° C.) (Bolton.) (Taken from paper by R. A. Bull.)

sloping lines marked 0.1 per cent, 1 per cent, etc., represent the loci of stress and temperature at which an equivalent flow occurs over a period of 10,000 hours.

Since steels usually have a coarser grain in the cast than in the rolled or forged state, it is assumed that large grain size is, at least partly, responsible for the greater resistance of cast steels to creep. Moreover, cast steel has in the full annealed condition shown a greater resistance to creep than when normalized or quenched and drawn, which again may be traced to the larger grains of the full annealed bars.

Figure 10 is a reproduction of curves by Bolton referred to in a paper by Bull(18), showing the creep at 900° F. (480° C.) of an annealed cast-carbon steel. It is interesting to note that the results of Bolton and Spring for the same type of steel at the same temperature and stress are in close agreement.

TABLE VIII.—THERMAL EXPANSION OF CARBON STEEL.

Type of Steel	Chemical Composition, per cent				Treatment	Linear Coefficient of Expansion per Degree Centigrade $\times 10^{-6}$ [a]				
	Carbon	Manganese	Sulfur	Phosphorus		0 to 100° C. (32 to 212° F.)	0 to 200° C. (32 to 390° F.)	0 to 300° C. (32 to 570° F.)	0 to 400° C. (32 to 750° F.)	0 to 500° C. (32 to 930° F.)
Cast	0.25 to 0.35	0.40 to 1.00	Under 0.05	Under 0.05	Cast annealed	11.9	12.9	13.3	14.0	14.7
Forged	0.20 to 0.30	0.40 to 0.80	Under 0.05	Under 0.05	Forged, quenched, drawn	12.2	12.8	13.4	14.0	14.7

[a] All values for Coefficient of Expansion are per degree Centigrade; to convert to corresponding values per degree Fahrenheit, multiply by $\frac{5}{9}$.

THERMAL EXPANSION OF REGULAR-GRADE CAST CARBON STEEL

Mochel(33) has given the average linear coefficient of expansion of cast carbon steel for temperature ranges up to 930° F. (500° C.). In reporting the values, those of a forged carbon steel are included to show the similarity of the two steels.

FIELDS OF APPLICATION FOR REGULAR-GRADE CARBON STEEL CASTINGS

The regular-grade carbon-steel castings represent the bulk of the steel foundry output and their use covers an extensive and varied field of application. This grade of castings gives very good results in either the normalized or quenched and drawn state. Moreover,

TABLE IX.—PROPERTIES OF HIGH-CARBON CAST STEEL, CARBON CONTENT ABOVE 0.35 PER CENT.

Steel	Chemical Composition, per cent					Mechanical Properties							Treatment of Steel[b]	Investigators
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Impact Values	Hardness Numbers[a]		
No. 1....	0.37	0.79	0.40	0.008	0.019	84 000	....	40 000	23.9	32.9	5[c]	....	As received........	Hall, Nissen, Taylor (11)
						82 000	....	50 000	26.7	49.9	10[c]	....	1650° F. (900° C.) (4), water quenched; 1260° F. (680° C.) (6), air cooled........	
						88 000	....	49 000	21.4	28.3	6[c]	....	1650° F. (900° C.) (4), air cooled; 1290° F. (695° C.) (6), air cooled........	
No. 2....	0.38	0.61	....	0.04	0.035	140 000	140 000	....	0	0	....	50 *S*	Water quenched, drawn 200° F. (95° C.)........	Grotts (10)
						122 000	118 000	....	5.0	8.0	....	46 *S*	Water quenched, drawn 800° F. (425° C.)........	
						113 000	100 000	....	7.5	12.0	....	42 *S*	Water quenched, drawn 1000° F. (540° C.)........	
						102 000	82 000	....	10.0	15.0	....	37 *S*	Water quenched, drawn 1200° F. (650° C.)........	
						98 000	73 000	....	14.0	21.0	....	33 *S*	Water quenched, drawn 1400° F. (760° C.)........	
						92 000	70 000	....	19.0	28.0	....	30 *S*	Water quenched, drawn 1600° F. (870° C.)........	
No. 3....	0.39	0.73	0.44	....	....	79 000	....	41 000	26.2	35.7	8.8[c]	....	1650° F. (900° C.) ($4\frac{1}{2}$), air cooled; 1290° F. (695° C. (6), furnace cooled........	Hall, Nissen, Taylor (11)
No. 4....	0.39	0.86	0.41	0.008	0.019	72 000	....	35 000	16.8	31.4	6.0[c]	....	As received........	
						86 000	....	51 000	23.5	38.7	24.5[c]	....	1650° F. (900° C.) (4), water quenched; 1260° F. (680° C.) (6), air cooled........	
						83 000	....	43 000	20.7	29.5	14.0[c]	....	1650° F. (900° C.) (4), air cooled; 1290° F. (695° C.) (6), air cooled........	
No. 5....	0.40	0.72	0.33	....	....	83 000	....	45 000	22.6	32.5	....	....	1650° F. (900° C.) furnace cooled........	Langenberg (21)
No. 6....	0.40	0.63	0.30	0.069	0.058	87 000	....	51 000	17.0	20.5	4.60[d]	182 *B*	1740° F. (950° C.) (2), air cooled, drawn 930° F. (500° C.) (4)	
No. 7....	0.41	0.61	0.27	0.065	0.075	83 000	....	52 000	7.5	9.5	2.40[d]	....	1740° F. (950° C.) (2), air cooled, drawn 930° F. (500° C.) (4)	
No. 8....	0.42	0.60	0.27	0.066	0.068	89 000	....	52 000	19.2	20.4	3.5[d]	....	1740° F. (950° C.) (2), air cooled, drawn 930° F. (500° C.) (4)	
No. 9....	0.42	0.65	0.28	0.069	0.043	88 000	....	52 000	18.2	20.4	5.5[d]	156 *B*	1740° F. (950° C.) (2), air cooled, drawn 930° F. (500° C.) (4)	
No. 10...	0.42	0.86	0.20	0.065	0.048	....	....	....	....	....	6.69[d]	....	1740° F. (950° C.) (2), air cooled, drawn 930° F. (500° C.) (4)	
No. 11...	0.42	0.86	0.20	0.065	0.104	....	....	....	....	....	3.41[d]	....	1740° F. (950° C.) (2), air cooled, drawn 930° F. (500° C.) (4)	
No. 12...	0.42	0.69	0.43	....	....	77 000	....	40 000	22.0	25.0	6.5[c]	....	1650° F. (900° C.) (4), furnace cooled........	Hall, Nissen, Taylor (11)
No. 13...	0.42	0.71	0.54	....	....	81 000	....	50 000	23.9	37.9	20.5[c]	....	1650° F. (900° C.) (4), oil quenched; 1250° F. (675° C.) (6), furnace cooled........	
No. 14...	0.42	0.71	0.54	....	....	82 000	....	51 000	26.4	44.2	17.7[c]	....	1650° F. (900° C.) (4), water quenched; 1250° F. (675° C.) (6), furnace cooled........	
No. 15...	0.44	0.93	0.56	0.032	0.042	....	....	....	....	....	10.01[d]	197 *B*	1650° F. air cooled........	Langenberg (21)
No. 16...	0.46	0.73	0.28	....	....	93 000	....	....	22.0	33.6	....	....	Annealed, furnace cooled........	Melmoth (9)
No. 17...	0.46	0.92	0.20	0.042	0.041	79 000	40 000	....	3.0	3.83	....	....	As cast........	Oberhoffer (7)
						85 000	40 000	....	7.07	8.00	....	....	1380° F. (750° C.) (6), furnace cooled........	
						89 000	50 000	....	7.50	8.73	....	....	1425° F. (775° C.) (6), furnace cooled........	
						88 000	48 000	....	7.57	8.43	....	....	1470° F. (800° C.) (6), furnace cooled........	
						87 000	48 000	....	6.17	7.00	....	....	1560° F. (850° C.) (6), furnace cooled........	
						89 000	46 000	....	7.07	8.30	....	....	1650° F. (900° C.) (6), furnace cooled........	

[a] The letter *B* designates Brinell hardness, and the letter *S*, Scleroscope hardness

[b] Numbers in parentheses correspond to number of hours at temperature.

[c] Frémont, kg-m.

[d] Charpy, ft-lb.

Steel	Chemical Composition, per cent					Mechanical Properties							Treatment of Steel[b]	Investigators
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Impact Values	Hardness Numbers[a]		
No. 18...	0.47	0.63	0.27	0.029	0.03	76 000	....	....	19.0	....	1.2[f]	....	1380° F. (750° C.) (12), slowly cooled	Giolitti (5)
						88 000	....	....	24.0	....	3.6[f]	....	1380° F. (750° C.) (12), slowly cooled; 1560° F. (850° C.) (7), air cooled	
No. 19...	0.48	0.68	0.41	0.01	0.019	83 000	....	39 000	22.6	27.1	7[c]	....	As received	Hall, Nissen, Taylor (11)
						88 000	....	52 000	24.9	41.9	10[c]	....	1650° F. (900° C.) (4), water quenched; 1250° F. (675° C.) (6), air cooled	
						91 000	....	54 000	21.3	29.5	8.5[c]	....	1650° F. (900° C.) (4), air cooled; 1290° F. (695° C.) (6), air cooled	
No. 20...	0.50	0.59	0.54	....	....	84 000	....	44 000	19.8	24.5	5.5[c]	....	1650° F. (900° C.) (4), furnace cooled	
No. 21...	0.51	0.56	0.38	....	....	83 000	....	42 000	19.5	19.2	5.8[c]	....	1650° F. (900° C.) (4), air cooled; 1400° F. (760° C.) (6), furnace cooled	
No. 22...	0.51	0.69	0.44	....	....	84 000	....	47 000	22.5	26.6	5.9[c]	....	1690° F. (920° C.) (5), air cooled; 1290° F. (695° C.) (6), furnace cooled	
No. 23...	0.53	0.28	0.22	0.046	0.058	81 000	31 000	28 000	16.1	15.9	1.3[f]	....	1725° F. (940° C.) (1¼), rapidly cooled to 1380° F. (750° C.), slowly cooled	Körber, Pomp (8)
No. 24...	0.53	0.79	0.25	0.036	0.027	87 000	35 000	28000	6.47	4.07	1.26[e]	213 *B*	As cast	Oberhoffer(7)
						79 000	35 000	26000	5.07	4.60	1.29[e]	200 *B*	1290° F. (695° C.) (6), furnace cooled	
						90 000	39 000	31 000	11.03	17.87	1.40[e]	194 *B*	1400° F. (760° C.) (6), furnace cooled	
						98 000	49 000	40 000	13.97	18.13	2.52[e]	198 *B*	1454° F. (790° C.) (6), furnace cooled	
						99 000	50 000	43 000	15.93	18.03	3.53[e]	208 *B*	1510° F. (820° C.) (6), furnace cooled	
						99 000	49 000	42 000	14.50	16.90	1.76[e]	212 *B*	1560° F. (850° C.) (6), furnace cooled	
						96 000	47 000	43 000	12.45	14.0	2.64[e]	209 *B*	1615° F. (880° C.) (6), furnace cooled	
						100 000	45 000	39 000	15.83	20.50	1.67[e]	211 *B*	1670° F. (910° C.) (6), furnace cooled	
						100 000	45 000	38 000	13.30	15.70	1.42[e]	219 *B*	1740° F. (950° C.) (6), furnace cooled	
						100 000	46 000	39 000	13.80	15.57	1.49[e]	215 *B*	1830° F. (1000° C.) (6), furnace cooled	
No. 25...	0.69	1.03	0.25	0.022	0.021	89 000	53 000	....	3.77	1.33	1.43[e]	245 *B*	As cast	
						87 000	38 000	....	7.03	4.70	1.34[e]	196 *B*	1290° F. (695° C.) (6), furnace cooled	
						108 000	47 000	....	7.47	7.93	1.40[e]	223 *B*	1345° F. (730° C.) (6), furnace cooled	
						111 000	47 000	....	6.63	7.90	1.25[e]	235 *B*	1400° F. (760° C.) (6), furnace cooled	
						110 000	48 000	....	9.63	9.33	1.15[e]	223 *B*	1450° F. (790° C.) (6), furnace cooled	
						110 000	47 000	....	8.10	7.80	1.68[e]	235 *B*	1510° F. (820° C.) (6), furnace cooled	
						106 000	49 000	....	4.93	3.63	1.48[e]	243 *B*	1830° F. (1000° C.) (6), furnace cooled	
No. 26...	0.86	0.90	0.27	0.028	0.016	71 000	43 000	....	1.40	0.37	1.35[e]	255 *B*	As cast	
						90 000	45 000	....	3.23	2.90	1.23[e]	241 *B*	1200° F. (650° C.) (6), furnace cooled	
						88 000	41 000	....	2.70	2.07	1.45[e]	239 *B*	1255° F. (680° C.) (6), furnace cooled	
						107 000	46 000	....	8.63	6.47	2.03[e]	215 *B*	1310° F. (710° C.) (6), furnace cooled	
						109 000	48 000	....	4.90	5.03	1.33[e]	236 *B*	1365° F. (740° C.) (6), furnace cooled	
						108 000	51 000	....	4.06	3.58	1.43[e]	253 *B*	1470° F. (800° C.) (6), furnace cooled	
						117 000	57 000	....	3.40	1.80	1.32[e]	271 *B*	1830° F. (1000° C.) (6), furnace cooled	

[a] The letter *B* designates Brinell hardness, and the letter *S*, Scleroscope hardness.
[b] Numbers in parentheses correspond to number of hours at temperature.
[c] Frémont, kg-m.
[e] Values in m-kg. per sq. cm.
[f] Specimen 30 by 30 by 160 mm. Cylindrical notch 4 mm. in diameter, 15 mm. deep. Values in m-kg. per sq. cm.

it is only necessary to properly heat treat the castings to extend their use into the fields now dominated by some of the alloy cast steels. Because of the many uses for castings of this grade, only some broad fields for their application will be given here.

Bolsters, side-frames, car couplers and other castings used by the railway industry represent a large part of the tonnage used. The machine tool manufacturers, the automobile industry and the heavy machinery builders are large purchasers of this class of steel. The oil refineries now use many plain carbon-steel castings in some of their oil stills which are operated at both high pressures and temperatures. Cast ornamental doors, windows and other decorative structural parts have replaced some of the hand-wrought iron.

The use of plain carbon steel castings can be increased if foundrymen pay more attention to quality of the product and take full advantage of the possibilities of heat treatment. By so doing, the inroads being made by other iron and steel products will be diminished and more uses found for the less costly but high quality regular-grade carbon steel casting.

HIGH-CARBON CAST STEEL

Cast steels containing above 0.35 per cent carbon are classified in the high-carbon grade. Although the uses for this steel are specialized, they can be extended if full advantage is taken of the possibilities of their heat treatment.

Properties at Room Temperature:

The mechanical properties at room temperature of several high-carbon cast steels are given in Table IX. The cast steels with carbon contents between 0.35 and 0.50 per cent have very good properties when either annealed or quenched and drawn. The elastic limit, the yield point, the tensile strength and the impact resistance are higher in the quenched-and-drawn steel. Trouble from quenching cracks may be lessened by cooling in oil or hot water. A quenching treatment is particularly applicable where castings of considerable strength and toughness are desired.

Langenberg(21) studied the effect of phosphorus content on the dynamic resistance of 0.40 to 0.44 per cent carbon steel. These steels are designated in Table IX as steels Nos. 6, 7, 8, 9, 10, 11 and 15. The influence of phosphorus was more apparent on the shock resistance than on the tensile strength. A most decided drop in the Charpy impact occurred with phosphorus contents between 0.06 and 0.07 per cent.

Properties of High-Carbon Steel at Low and Elevated Temperatures:

The mechanical properties at elevated temperatures of a 0.53 per cent carbon steel are given in Table X. The results were taken from the work of Körber and Pomp(8) on the mechanical properties of cast steel at high temperatures. Between 400 and 600° F. (205 and 315° C.) the elongation and reduction of area values showed a pronounced drop, while the impact results indicated no embrittlement at these temperatures.

TABLE X.—PROPERTIES OF HIGH-CARBON CAST STEEL (0.53 PER CENT CARBON) AT ELEVATED TEMPERATURES BY THE SHORT-TIME TEST.

Steel	Mechanical Properties	Temperature of Tests					
		70° F. (21° C.)	212° F. (100° C.)	390° F. (200° C.)	570° F. (300° C.)	750° F. (400° C.)	930° F. (500° C.)
No. 23.....	Tensile strength, lb. per sq. in............	81 000	75 000	71 000	75 000	71 000	43 000
	Yield point, lb. per sq. in................	31 000	29 000	27 000	25 000	24 000	20 000
	Elastic limit, lb. per sq. in................	28 000	29 000	25 000	19 000	16 000	12 000
	Elongation, per cent......................	16.1	17.9	14.9	9.3	13.7	31.2
	Reduction of area, per cent..............	15.9	19.1	18.3	12.2	14.8	35.1
	Impact, m-kg. per sq. cm..................	1.3	3.6	5.4	5.1	4.9	3.4

TABLE XI.—THE ENDURANCE PROPERTIES OF 0.53 PER CENT CARBON CAST STEEL[a] AT ELEVATED TEMPERATURES.

Each endurance series was carried to 10,000,000 or more cycles, unbroken.

	Temperature of Tests				
	60° F. (16° C.)	212° F. (100° C.)	570° F. (300° C.)	930° F. (500° C.)	1110° F. (600° C.)
Tensile strength, lb. per sq. in...............	99 000	92 000	95 000	58 000	38 000
Yield point, lb. per sq. in....................	50 000	49 000	....	....	....
Proportional limit, lb. per sq. in.............	38 000	41 000	23 000	14 000	....
Modulus of elasticity, lb. per sq. in..........	3 000 000	2 900 000	2 700 000	1 800 000	....
Elongation, per cent...........................	15	21	11	30	41
Reduction of area, per cent....................	17	23	17	38	48
Limiting creep stress, lb. per sq. in..........	....	....	55 000	....	....
Endurance limit, lb. per sq. in................	27 400	29 000	29 200	19 500	15 700
Endurance ratio................................	0.28	0.32	0.31	0.32	0.41

[a] Chemical Composition: Carbon, 0.53; manganese, 0.69; silicon, 0.45; sulfur, 0.026; phosphorus, 0.027; nickel, 0.17; chromium, 0.09 per cent.

Endurance Limit of a 0.53 per cent Carbon Cast Steel at Elevated Temperatures.—Tapsell and Clenshaw(18) reported tests at elevated temperatures of a 0.53 per cent carbon steel. The results are summarized in Table XI.

The endurance limit of the cast steel at room temperature was lower than one would anticipate from known endurance ratios for cast steels. It is interesting to note that the endurance ratio increases at temperatures above 1000° F. (540° C.). Tapsell and Clenshaw's endurance limits at 930 and 1110° F. (500 and 600° C.) are very likely too high, since above 800° F. (425° C.) steel acts like a nonferrous alloy in endurance and will probably require hundreds of millions of cycles to obtain its limit.

A curve of values for the modulus of elasticity for this steel shows a uniform decrease from 30,000,000 lb. per sq. in. at normal temperature to 25,000,000 lb. per sq. in. at 800° F. (425° C.). At higher temperatures the values for the modulus of elasticity decrease sharply.

Fields of Application for High-Carbon Cast Steel:

The high-carbon steel castings, if properly cast and heat treated, are particularly applicable for services requiring considerable strength and toughness. There is no advantage in making this grade of steel, unless its mechanical properties or its hardness are to be developed through heat treatment.

TABLE XII.—PROPERTIES OF COMMERCIAL STEEL CASTINGS.

Steel	Chemical Composition, per cent			Tensile Properties			
	Carbon	Manganese	Silicon	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent
Average	0.24	0.71	0.33	73 130	41 915	30.5	48.5
Low	0.16	0.61	0.30	68 000	40 500	25.0	39.1
High	0.30	0.83	0.37	87 000	53 000	36.0	62.5

Specific uses for the high-carbon steel castings are to be found in roll and die-tool manufacture, machine tools, automotive and railroad equipment.

QUALITY OF PLAIN-CARBON CAST STEEL

The tensile properties of carbon steel castings of normal silicon, manganese, sulfur and phosphorus contents are linearly related to the carbon content for values in the range of 0.10 to 0.60 per cent. The tensile strength, the elastic limit, and the yield point are higher and the elongation and the reduction of area are lower with higher carbon contents.

The properties of 59 heats of annealed carbon cast steel representing production in a commercial foundry were summarized in a paper by J. D. Fenstermacher(34). Average mechanical properties of the steels are given in Table XII.

It should not be inferred that Table XII shows high and low values concurrently obtained, either in chemical analysis or in tension testing. There was one heat only that contained as much as 0.30

per cent carbon. Because other conditions related to composition as regularly determined and possibly to other partially controlling factors, this highest carbon heat did not develop the highest tensile strength listed in the summary.

The summary illustrated the ability of commercial foundries to produce steel castings uniform in quality and equivalent in properties to steel made in carefully controlled laboratory tests.

The effects of the elements silicon, manganese, sulfur and phosphorus, though occasionally ignored, are important. Silicon and manganese not only insure sound castings but, as alloying elements, influence the properties of the steel quite definitely. Skill in melting (which may or may not be indicated by conventional analysis) is, of course, a vital factor. It is much more important than the type of furnace used. The methods of heat treatment employed and the care with which they are performed are outstanding in their influence on properties of sound carbon-steel castings. The unfavorable influences of the cast structure may be overcome by either a simple full anneal or a normalizing treatment. Although such treatment results in material benefits, the most desirable heat treatment from the standpoint of mechanical properties and machineability of the castings requires a quench and a draw.

Oehler(35) measured the tensile strength, the yield point, and the elongation of low-carbon, regular-grade, and high-carbon cast steels made in the open-hearth, the converter, and the electric furnaces. He compared the quality of these steels on the basis of the quality coefficient, that is the product of the tensile strength in kilograms per square millimeter and the elongation in per cent. Oehler concludes that cast steel melted in the electric furnace is superior to that made in the open-hearth or the converter.

Melmoth(36) used the more complicated formula of J. D. Cutter for expressing the quality of cast steels. This formula involves all the properties shown by the tension test. Melmoth's tests show no conclusive evidence as to the superiority between electric-furnace and open-hearth cast steel.

MEDIUM-MANGANESE CAST STEEL

Cast steel of 1.00 to 2.00 per cent manganese and 0.20 to 0.50 per cent carbon contents is not strictly an alloy steel in the sense of containing another alloying element than the five ordinarily determined constituents. Hall(3,37,39), prominent in its development, describes it variously as pearlitic-manganese steel, intermediate manganese steel, and as high-manganese steel, the latter name

TABLE XIII.—PROPERTIES OF MEDIUM-MANGANESE CAST STEEL.

Steel	Chemical Composition, per cent					Mechanical Properties						Treatment of Steel[e]	References
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Tensile Strength, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Impact Values	Brinell Hardness Numbers		
No. 1	0.25	1.43	0.55	....	....	92 000	62 000	24.1	53.2	30[c]	....	1650° F. (900° C.) (4), water quenched; 1185° F. (640° C.) (6), furnace cooled	Hall, Nissen, Taylor(11)
No. 2	0.26	1.11	0.45	....	....	78 000	51 000	30.5	56.4	25.6[c]	....	1650° F. (900° C.) (4), water quenched; 1290° F. (695° C.) (6), furnace cooled	
No. 3	0.26	1.36	0.51	....	....	96 000	65 000	25.6	57.2	15.0[c]	....	1650° F. (900° C.) (4), water quenched; 1185° F. (640° C.) (6), furnace cooled	
No. 4	0.28	1.40	0.53	....	....	83 000	53 000	29.6	57.9	27.5[c]	....	1650° F. (900° C.) (4), water quenched; 1220° F. (660° C.) (6), furnace cooled	
No. 5	0.26	1.76	0.54	....	....	85 000	57 000	24.7	41.0	30.0[c]	....	1650° F. (900° C.) (4), water quenched; 1290° F. (695° C.) (6), furnace cooled	
						76 000	44 000	30.4	50.4	17.5[c]	....	1650° F. (900° C.) (4), air cooled; 1290° F. (695 °C.) (6), furnace cooled	
No. 6	0.31	1.12	0.52	....	....	81 000	52 000	29.5	56.9	28.4[c]	....	1650° F. (900° C.) (4), water quenched; 1290° F. (695° C.) (6), air cooled	
No. 7	0.31	1.32	0.40	....	....	98 000	63 000[a]	27.0	53	13.3[d]	212	1650° F. (900° C.) (3), air cooled	Zuege(38)
						88 000	55 000[a]	30	57.3	14.2[d]	183	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.) (3), air cooled	
No. 8	0.32	1.42	0.40	....	....	92 000	58 000[a]	26.0	45.4	13.9[d]	192	1650° F. (900° C.) (3), air cooled	
						83 000	55 000[a]	31.5	55.7	16.4[d]	166	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.) (3), air cooled	
No. 9	0.33	1.50	0.38	....	....	104 000	61 000[a]	23.5	49.5	11.2[d]	212	1650° F. (900° C.) (3), air cooled	
						89 000	51 000[a]	28.0	58.3	13.3[d]	183	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.) (3), air cooled	
No. 10	0.35	1.38	0.33	....	....	84 000	47 000	24.5	35.1	....	....	1650° F. (900° C.) (4), air cooled; 1290° F. (695° C.) (6), air cooled	Hall, Nissen, Taylor(11)
						106 000	74 000	17.7	34.0	....	....	1650° F. (900° C.) (4), water quenched; 1290° F. (695° C.) (6), air cooled	

[a] Yield point, lb. per sq. in.

[c] Frémont values in kilogram meters of work absorbed in breaking standard Frémont bar.

[d] Charpy, ft-lb..

[e] Numbers in parentheses correspond to number of hours at temperature.

TABLE XIII.—*Continued.*

Steel	Chemical Composition, per cent					Mechanical Properties						Treatment of Steel[e]	References
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Tensile Strength lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Impact Values	Brinell Hardness Numbers		
No. 11.......	0.35	1.42	0.40	....	....	101 000	62 000[a]	22.5	45.3	8.3[d]	228	1650° F. (900° C.) (2), air cooled	Zuege(38)
						144 000	101 000[a]	8.0	22	2.8[d]	321	1650° F. (900° C.) (2), air cooled; 1550° F. (840° C.) (2), oil quenched; drawn 600° F. (315° C.)	
						131 000	92 000[a]	13.2	34.3	7.9[d]	286	1650° F. (900° C.) (2), air cooled; 1550° F. (840° C.) (2), oil quenched; drawn 900° F. (480° C.)	
						101 000	73 000[a]	21.5	50.7	14.4[d]	228	1650° F. (900° C.) (2), air cooled; 1550° F. (840° C.) (2), oil quenched; drawn 1200° F. (650° C.)	
						98 000	58 000[a]	23.7	52.3	23.6[d]	187	1650° F. (900° C.) (2), air cooled; 1550° F. (840° C.) (2), oil quenched; drawn 1350° F. (735° C.)	
No. 12.......	0.37	1.44	0.28	....	....	99 000	61 000[a]	20.0	32.8	4.1[d]	202	1650° F. (900° C.) (3), air cooled	
						94 000	58 000[a]	24.5	49.7	4.5[d]	170	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.) (3), air cooled	
No. 13.......	0.35	1.71	0.30	0.030	0.021	81 000	39 000[b]	2.1	4.0	2.8[d]	179	As received, cast structure	Moore(15)
						109 000	42 000[b]	14.4	26.0	20.2[d]	197	1650° F. (900° C.) (1), air cooled; 1525° F. (830° C.) (1), air cooled	
						104 000	47 000[b]	25.1	56.0	28.4[d]	196	1650° F. (900° C.) (1), air cooled; 1525° F. (830° C.) (1), air cooled; 600° F. (315° C.) (1), air cooled	
						104 000	60 000[b]	22.5	48.0	30.7[d]	188	1650° F. (900° C.) (1), air cooled; 1525° F. (830° C.) (1), air cooled; 1000° F. (540° C.) (1), air cooled	
						108 000	48 000[b]	13.7	23.0	22.1[d]	201	1525° F. (830° C.) (1), air cooled	
						104 000	49 000[b]	25.0	53.0	28.7[d]	192	1525° F. (830° C.) (1), air cooled; 600° F. (315° C.) (1), air cooled	
						103 000	59 000[b]	26.8	56.0	32.3[d]	196	1525° F. (830° C. (1), air cooled; 600° F. (315° C.) (1), air cooled; 1000° F. (540° C.) (1), air cooled	
						104 000	56 000[b]	23.4	53.0	28.8[d]	199	1650° F. (900° C.) (1), air cooled; 1525° F. (830° C.) (1), air cooled; 875° F. (470° C.) (1), air cooled	
No. 14.......	0.36	2.42	0.24	0.073	0.041	106 000	54 000	14.0	19.4	5.5[c]	....	1650° F. (900° C.), air cooled; 1290° F. (695° C.) (6), air cooled	Hall, Nissen, Taylor(11)

[a] Yield point, lb. per sq. in.
[b] Proportional limit, lb. per sq. in.
[c] Frémont values in kilogram meters of work absorbed in breaking standard Frémont bar.
[d] Charpy, ft-lb.
[e] Numbers in parentheses correspond to number of hours at temperature.

differentiating it from Hadfield or regular-manganese steel, which contains 12 or more per cent manganese and more than 1 per cent carbon. We have chosen to call it medium-manganese cast steel to remove confusion that may arise in its identification later.

Steels of this composition are largely used for purposes where a combination of high strength with great toughness is essential. The tensile strength and elastic limit rise slowly with the manganese content, while the elongation and reduction of area decrease slightly. Castings of this steel possess greater toughness and more resistance to shock than the higher carbon castings of similar strength. The mechanical properties of fourteen medium-manganese cast steels are given in Table XIII. The steels are arranged in order of equivalent carbon contents with increasing manganese. Most of the results taken from the publications by Hall substantially agreed with results of tests on routine heats given by Zuege(38) and by Lorenz(40). The high strength and great toughness were developed by quenching in water or oil and by drawing the steel to increase the ductility and impact values. The choice of the drawing temperature is determined by the uses to which the castings are put. Castings of this steel seldom crack on quenching. Full annealed castings of this grade are more brittle than the annealed plain carbon steels.

TABLE XIV.—ENDURANCE PROPERTIES OF MEDIUM-MANGANESE CAST STEEL.

Steel	Carbon, per cent	Manganese, per cent	Tensile Strength, lb. per sq. in.	Endurance Limit, lb. per sq. in.	Endurance Ratio	Heat Treatment
No. 11...	0.35	1.42	101 000	41 000	0.41	1650° F. (900° C.)
			144 000	57 000	0.40	1650° F. (900° C.); 1550° F. (840° C.), oil quenched; 600° F. (315° C.)
			131 000	51 000	0.39	1650° F. (900° C.); 1550° F. (840° C.), oil quenched; 900° F. (485° C.)
			101 000	46 000	0.46	1650° F. (900° C.); 1550° F. (840° C.), oil quenched; 1200° F. (650° C.)
			98 000	42 000	0.43	1650° F. (900° C.); 1550° F. (840° C.), oil quenched; 1350° F. (735° C.)
No. 13...	0.35	1.71	81 000	32 000	0.40	As cast
			109 000	45 000	0.41	1650° F. (900° C.); 1525° F. (830° C.)
			104 000	45 000	0.43	1650° F. (900° C.); 1525° F. (830° C.); 600° F. (315° C.)
			104 000	45 000	0.43	1650° F. (900° C.); 1525° F. (830° C.); 1000° F. (540° C.)
			108 000	48 000	0.45	1525° F. (830° C.)
			104 000	44 000	0.42	1525° F. (830° C.); 600° F. (315° C.)
			103 000	43 000	0.42	1525° F. (830° C.); 1000° F. (540° C.)
			104 000	44 000	0.42	1650° F. (900° C.); 1525° F. (830° C.); 875° F. (470° C.)

According to Zuege(41), cast steels with carbon in the range of 0.27 to 0.37 per cent and manganese of 1.35 to 1.55 per cent have the following mechanical properties:

	NORMALIZED AT 1650° F. (900° C.)	NORMALIZED AT 1650° F. (900° C.), DRAWN AT 1250° F. (675° C.)
Tensile strength, lb. per sq. in.	95 000	85 000
Yield point, lb. per sq. in.	60 000	52 000
Elongation in 2 in., per cent	20.0	24.0
Reduction of area, per cent	40.0	45.0

To produce increased toughness at the sacrifice of strength, a carbon content of 0.22 to 0.32 per cent with a manganese content of 1.15 to 1.35 per cent is sometimes used. Langenberg(21) determined the impact properties of castings having different carbon and manganese contents and found that unusual Charpy impact values are obtained in normalized specimens when the carbon does not exceed 0.30 per cent and the manganese 1.31 per cent. He believed that any increase in carbon above 0.30 per cent or in manganese above 1.30 per cent decreased the Charpy value. Hall(37), on the other hand, claimed that his tests did not bear out the conclusions of Langenberg. In a summary of 1800 tests on quenched-and-drawn steels containing more than 1.30 per cent manganese, Hall found that the impact values varied over a wide range, but that in general excellent resistance to impact is offered by steels containing substantially higher quantities of carbon and manganese than the limits set by Langenberg. It should be pointed out that these investigators were

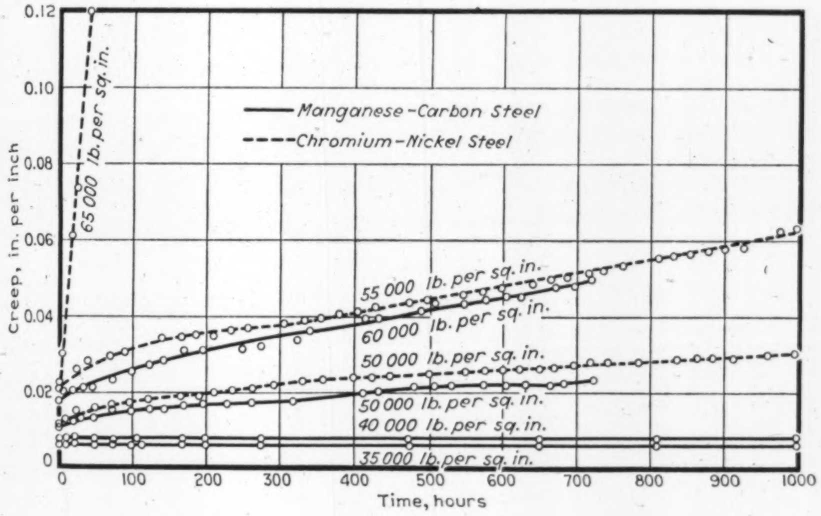

FIG. 11.—Creep Tests on Cast Steel at 700° F. (370° C.). (Zuege.)

dealing with steels of different heat treatments and, while Langenberg had set certain limits for the carbon and manganese contents, his steels were normalized. Hall on the other hand was working with

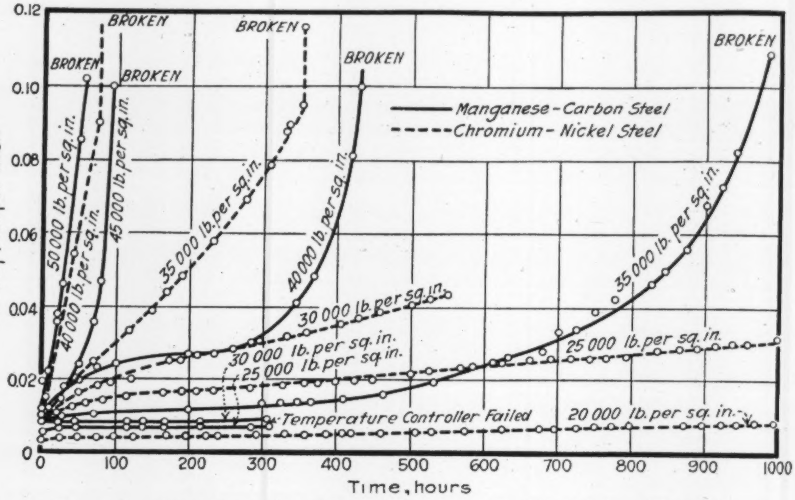

FIG. 12.—Creep Tests on Cast Steel at 850° F. (455° C.). (Zuege.)

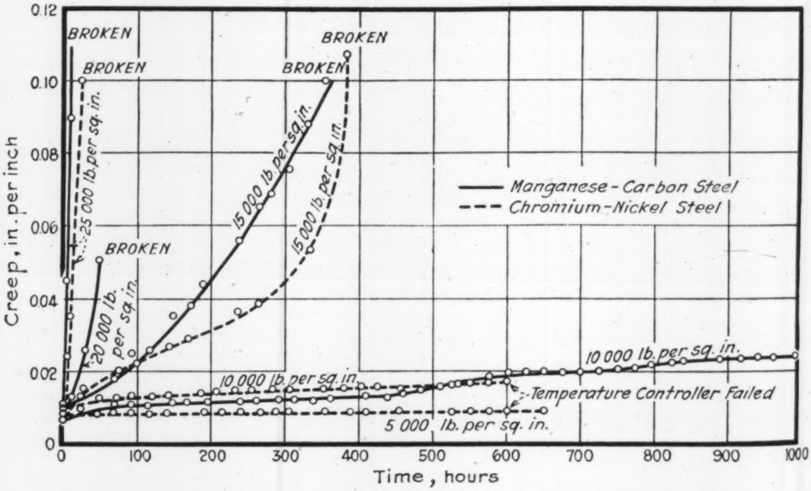

FIG. 13.—Creep Tests on Cast Steel at 1000° F. (540° C.). (Zuege.)

quenched-and-drawn steels which in a sense do not permit a direct comparison with Langenberg's results. The Charpy values reported by Moore(15) for normalized and normalized-and-drawn steel with 0.35 per cent carbon and 1.71 per cent manganese lend support to the conclusions of Hall. The latter believes that with the proper carbon content the manganese can be successfully carried considerably higher than is now generally assumed.

Endurance Properties of Medium-Manganese Cast Steel:

Both Moore(15) and Zuege(38) have reported endurance tests on this type of steel. Their results are given in Table XIV. A more complete summary of the mechanical properties and a description of the heat treatment given these steels are presented in Table XIII.

The endurance ratio for cast steels is somewhat lower than the average obtained for wrought materials. Sufficient data are not available to indicate a variation in endurance ratio with heat treatment. However, the value for the oil-quenched specimen drawn at 1200° F. (650° C.) is greatest. This may point to a slight increase in the ratio for quenched-and-drawn cast materials, a factor which Mitchell(20) noted in his endurance studies of the regular-grade carbon cast steel.

Creep Tests on Medium-Manganese Cast Steel:

The only observations on creep tests of medium-manganese steel that came to our attention appeared in papers by Bull(18) and by Müller and Piwowarsky(24). Bull reported data furnished by D. Zuege of creep tests at 700, 850 and 1000° F. (370, 455 and 540° C.), on medium-manganese cast steel and chromium-nickel cast steel of the following compositions:

	CARBON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT	PHOSPHORUS, PER CENT	SULFUR, PER CENT	CHROMIUM, PER CENT	NICKEL, PER CENT
Medium-manganese steel.	0.35	1.42	0.40	0.038	0.045	....	....
Chromium-nickel steel....	0.48	0.70	0.45	0.024	0.043	0.80	1.24

Both steels were heated at 1650° F. (900° C.) for three hours and cooled in air. The chromium-nickel steel was given an additional draw treatment at 1275° F. (690° C.). The tensile properties of the two steels at room temperature are given below:

	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
Medium-manganese steel.........	101 000	59 500	22.0	43.6
Chromium-nickel steel...........	114 000	61 000	20.0	35.5

The test results are shown in Figs. 11, 12 and 13.

Bull pointed out that these results on two well-known low-alloy steels indicated the desirability of additional testing before drawing definite conclusions as to comparative performances.

Müller and Piwowarsky(24) gave creep strength limits on a single medium-manganese cast steel containing 0.36 per cent carbon, 0.42 per cent silicon, 1.96 per cent manganese, and 0.046 per cent phosphorus. The stresses at 572, 752 and 932° F. (300, 400 and 500° C.) required to attain an elongation of 0.003 per cent per hour during the tenth and fifteenth hours, taken from a curve of values, are roughly as follows:

TEMPERATURE	CREEP STRENGTH, LB. PER SQ. IN.
572° F. (300° C.)	33 000
752° F. (400° C.)	26 000
932° F. (500° C.)	8 000

This steel was somewhat superior in its creep resistance to a plain carbon steel of 0.36 per cent carbon and to another steel containing 0.18 per cent carbon and 2.21 per cent chromium. One must use caution, however, in accepting values from accelerated creep tests.

Field of Application of Medium-Manganese Cast Steel:

The customary range of analysis of the medium-manganese cast steels that can be treated by either quenching in oil or water and drawing, or normalizing and drawing, is 0.20 to 0.40 per cent carbon, 0.20 to 0.50 per cent silicon, and 1.10 to 2.00 per cent manganese. When properly heat treated this grade of steel has excellent ductility and tensile properties and good resistance to abrasion. It is used extensively for excavating buckets and dipper teeth, caterpillar shoes, truck wheels, treads on tractors, and for purposes where high strength, toughness and wear-resistance are paramount.

NICKEL-MANGANESE CAST STEELS

Manganese added to nickel cast steels gives a product with excellent properties without a large increase in cost. Carbon contents of nickel-manganese steels with 1.00 to 1.75 per cent nickel and 1.00 to 1.50 per cent manganese are usually in the range of 0.30 to 0.40 per cent. When great hardness or strength is required, a higher carbon content is used, and when ductility and toughness are the main considerations, a lower carbon content is required.

Few data have been published on the mechanical properties of the nickel-manganese steels. McKnight(42) gave the following mechanical properties of an annealed nickel-manganese steel of 0.30 to 0.40 per cent carbon content:

Tensile strength, lb. per sq. in.	80 000 to 90 000
Elastic limit, lb. per sq. in.	50 000 to 60 000
Elongation in 2 in, per cent	18 to 23
Reduction of area, per cent	28 to 33

These values are considered low but can be increased if the steel is given a suitable heat treatment. A homogenizing treatment at 1550 to 1700° F. (840 to 925° C.), and in some instances as high as 1800° F. (980° C.), is recommended. By such treatment the coarse dendritic structure of the cast steel is broken up and replaced by a finer-grained homogeneous mixture of pearlite and ferrite. The structure may be further refined by reheating to a lower temperature, while the stresses set up during cooling may be relieved by a draw.

Zima(43) compared the properties of a medium-manganese steel with those of a nickel-manganese steel of like carbon content. The chemical composition of the two steels was as follows:

	Carbon, per cent	Nickel, per cent	Manganese, per cent	Silicon, per cent
Steel A	0.25 to 0.35	1.00 (min.)	1.00 (1.20 max.)	0.30 to 0.40
Steel B	0.25 to 0.35	....	1.35 to 1.50	0.30 to 0.40

These steels, after being normalized at 1650° F. (900° C.) and drawn at 1200° F. (650° C.), gave the following average properties:

	Steel A	Steel B
Tensile strength, lb. per sq. in.	85 000 to 105 000	80 000 to 100 000
Elastic limit, lb. per sq. in.	55 000 to 65 000	50 000 to 60 000
Elongation in 2 in., per cent	22 to 25	18 to 22
Reduction of area, per cent	45 to 50	26 to 40
Brinell hardness numbers	175 to 180	185 to 190
Izod impact, ft-lb	40 to 45	20 to 25

The impact properties of a nickel-manganese steel were determined at Battelle Memorial Institute for the Ohio Steel Foundry Co.[1] The analysis of this steel follows: 0.33 per cent carbon, 1.08 manganese, 0.40 silicon, and 1.18 nickel.

Alternate Charpy impact specimens 2 in. long and 0.394 in. square, having a 45-deg. V-notch 0.079 in. deep, were cut from blocks of cast steel 3 by 3 by $2\frac{1}{4}$ in. in dimensions, following a quench and draw and a normalizing treatment. These blocks were taken from 6 by 6 by 24 in. castings. The impact and Brinell hardness values were as follows:

Specimen	Charpy Impact, ft-lb.	Brinell Hardness Numbers	Heat Treatment[a]
No. 1	40.0	231	1560° F. (850° C.) (1), water quenched; 1200° F. (650° C.), air cooled
No. 2	20.0	192	1580° F. (860° C.) (1), air cooled
No. 3	23.6	170	1580° F. (860° C.) (1), air cooled; 1200° F. (650° C.), air cooled

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[a] Numbers in parentheses correspond to number of hours at temperature.

[1] Published through the courtesy of the Ohio Steel Foundry Co.

The best impact properties are developed when this steel is in the heat-treated condition.

Hall, Nissen and Taylor(11) made several cast steels to determine if part of the nickel in a nickel steel could be replaced by manganese. Their selected compositions are not those normally applying to nickel-manganese cast steel, but their results are worth considering as a rough comparison with properties of steels made on a commercial scale. Results of tests of three of these steels are as follows:

	Chemical Composition, per cent				Mechanical Properties					
	Carbon	Silicon	Manganese	Nickel	Tensile Strength, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Frémont Impact, kg-m.	Heat Treatment[a]
Nickel Steel No. 1	0.21	0.36	0.47	2.36	81 000	62 000	24.7	41.9	15.5	1650° F. (900°C.) (3), water quenched, drawn 1185° F. (640° C.) (8½)
Nickel Steel No. 2	0.24	0.29	0.87	3.63	91 000	67 000	24.0	22.1	14.0	1650° F. (900° C.) (3), water quenched, drawn 1255° F. (680° C.) (8)
Nickel-Manganese Steel	0.30	0.48	1.44	2.30	114 000	64 000	15.7	25.5	14.0	1650° F. (900° C.) (3), water quenched, drawn 1255° F. (680° C.) (8)

[a] Numbers in parentheses correspond to number of hours at temperature.

These results indicate that the nickel-manganese steel compares favorably in impact with the nickel steels and is superior to them in tensile strength, although its higher carbon content might account in part for this.

Rys(44) gave the following mechanical properties for a quenched nickel-manganese cast steel containing 0.25 per cent carbon, 1 per cent nickel and 1 per cent manganese:

Tensile strength, lb. per sq. in.	78 000
Elastic limit, lb. per sq. in.	43 000
Elongation ($l = 5\,d$), per cent	16.5
Reduction of area, per cent	45
Impact, m-kg. per sq. cm	8

Hall(39) recorded properties of a series of nickel-manganese steels containing from 0.20 to 0.85 per cent copper. His results showed that the presence of copper undoubtedly increases the tensile strength, the yield point and the Brinell hardness of these steels. The results, taken from the paper by Hall, are given in Table XV. The heat treatment given these steels was not described. The mechanical properties of these nickel-manganese-copper steels compared favorably with those of a 3 per cent nickel steel.

TABLE XV.—PROPERTIES OF NICKEL-MANGANESE-COPPER CAST STEEL.

Chemical Composition, per cent				Mechanical Properties			
Carbon	Manganese	Nickel	Copper	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent
0.36	0.81	1.60	0.76	92 000	56 000	22	37
0.33	1.02	1.15	0.49	89 000	54 000	25	40
0.27	1.02	1.47	0.42	86 000	56 000	23	34
0.36	1.18	1.37	0.80	94 000	51 000	23	36
0.36	1.03	1.47	0.63	90 000	55 000	23	34
0.36	1.03	1.73	0.21	96 000	59 000	25	41
0.31	1.15	1.80	0.62	92 000	55 000	23	36

TABLE XVI.—COMPOSITION OF SILICON CAST STEEL.

	Designation	Chemical Composition, per cent						
		Carbon	Silicon	Manganese	Phosphorus	Sulfur	Copper	Titanium
Plain carbon steel	C	0.39	0.45	0.81	0.026	0.049	0.11	....
Silicon steel	D	0.18	0.73	1.10	0.038	0.04	0.13	....
Silicon steel	A	0.18	0.76	1.10	0.030	0.029	0.10	....
Silicon steel with copper	H	0.14	1.01	0.73	0.015	0.041	0.30	....
Silicon steel with titanium	B	0.16	1.17	0.76	0.020	0.025	0.09	0.13
Silicon steel	F	0.17	1.11	1.11	0.030	0.042	0.12	....
Silicon steel	E	0.18	1.30	1.22	0.046	0.040	0.13	....

TABLE XVII.—PROPERTIES OF SILICON STEEL AT ROOM TEMPERATURE.

Steel	Heat Treatment	Mechanical Properties				
		Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Impact Resistance, m-kg. per sq. cm.
C	Unannealed	75 000	....	17	18	1.4
	Annealed, furnace cooled	80 000	43 000	15	19	3.8
	Annealed, air cooled	77 000	45 000	13	18	4.5
D	Unannealed	68 000	....	29	54	2.9
	Annealed, furnace cooled	70 000	41 000	32	60	6.4
	Annealed, air cooled	74 000	45 000	30	55	9.7
A	Unannealed	71 000	....	27	48	1.3
	Annealed, furnace cooled	78 000	50 000	32	40	7.2
	Annealed, air cooled	77 000	50 000	20	35	9.3
H	Unannealed	68 000	....	31	49	2.4
	Annealed, furnace cooled	70 000	45 000	32	60	6.8
	Annealed, air cooled	74 000	47 000	28	48	8.3
F	Unannealed	70 000	....	22	42	1.4
	Annealed, furnace cooled	71 000	45 000	27	54	5.3
	Annealed, air cooled	75 000	51 000	25	52	8.6
B	Unannealed	71 000	....	27	50	0.9
	Annealed, furnace cooled	72 000	47 000	24	41	5.9
	Annealed, air cooled	74 000	51 000	22	42	7.5
E	Unannealed	75 000	....	27	44	0.9
	Annealed, furnace cooled	77 000	51 000	27	45	3.9
	Annealed, air cooled	84 000	57 000	26	38	5.9

Fields of Application of Nickel-Manganese Cast Steel:

Nickel manganese cast steel fills a need for a relatively cheap alloy steel with good mechanical properties. If heat treated, this type of steel gives good tensile characteristics with marked shock-resisting power. It is used for electrical machinery castings and for highly stressed machine parts.

SILICON CAST STEEL

Wrought silicon steels for structural members have been in general use for some time, but the cast silicon steels have been made only in small tonnages in America. Very recently Schulz and Bonsmann(45) published some interesting data on six silicon cast steels of medium-manganese and low-carbon content and compared their properties with a plain carbon steel containing 0.39 per cent carbon. The compositions and properties at room temperature are given in Tables XVI and XVII. The silicon steels exhibit a high degree of plastic deformation. These steels show an elongation and a reduction of area about 60 per cent higher and a notch impact resistance about 80 per cent higher than those for the plain carbon steels of slightly higher tensile strength. The authors point out that the improved properties are not alone the result of silicon, but that they are also influenced by the higher manganese content. The properties of the silicon cast steels are greatly improved by full annealing; however, better properties are secured with air-cooled specimens than with those cooled in the furnace. For proper heat treatment, these steels should be heated 200 to 300° F. (110 to 165° C.) higher than the plain carbon steels because of the influence of silicon on the transformation temperature.

Compared with the others, steel H which contained copper, showed remarkable resistance to corrosion in 1 per cent HCl, 1 per cent H_2SO_4, and 5 per cent formic acid, but only equivalent results in sea water.

Rys(44) gives the following average properties of heat-treated silicon steels having an average composition of 0.40 per cent carbon, 1.50 per cent silicon and 0.50 per cent manganese:

Tensile strength, lb. per sq. in.	110 000
Elastic limit, lb. per sq. in.	68 000
Elongation ($l = 5d$), per cent	18
Reduction of area, per cent	30

Such steels are tough and strong and are said to have a high resistance to wear.

Barton(46) states that silicon increases the wear resistance of steels without increasing the machining difficulties and that silicon

TABLE XVIII.—PROPERTIES OF SILICON CAST STEEL AT LOW AND ELEVATED TEMPERATURES.

Steel	Chemical Composition, per cent						Mechanical Properties	Temperature of Test								
	Carbon	Silicon	Manganese	Phosphorus	Sulfur	Copper		−112° F. (−80° C.)	−4° F. (−20° C.)	32° F. (0° C.)	68° F. (20° C.)	212° F. (100° C.)	392° F. (200° C.)	572° F. (300° C.)	752° F. (400° C.)	932° F. (500° C.)
No. 1	0.20	0.84	0.90	0.034	0.033	0.17	Tensile strength, lb. per sq. in.	.....	.....	....	75 000	70 000	67 000	69 000	65 000	47 000
							Yield point, lb. per sq. in.	.....	.....	....	40 000	36 000	32 000	29 000	27 000	23 000
							Elastic limit, lb. per sq. in.	.....	.....	....	38 000	36 000	31 000	24 000	19 000	13 000
							Elongation, per cent	.....	.....	....	25.5	26.4	22.4	21.2	21.4	32.4
							Reduction of area, per cent	.....	.....	....	39.8	41.4	42.2	35.7	37.1	48.5
							Impact, m-kg. per sq. cm.	.....	.....	....	3.3	8.7	10.1	9.4	9.3	6.3
No. 2	0.10	0.92	0.74	0.051	0.039	0.20	Tensile strength, lb. per sq. in.	.....	.....	....	65 000	60 000	62 000	60 000	59 000	41 000
							Yield point, lb. per sq. in.	.....	.....	....	32 000	29 000	27 000	24 000	22 000	21 000
							Elastic limit, lb. per sq. in.	.....	.....	....	27 000	28 000	27 000	19 000	17 000	16 000
							Elongation, per cent	.....	.....	....	33.4	32.2	21.8	24.3	25.5	38.2
							Reduction of area, per cent	.....	.....	....	55.5	56.3	52.0	52.1	51.7	59.6
							Impact, m-kg. per sq. cm.	.....	.....	....	1.7	9.7	14.3	14.7	14.9	10.6
C Annealed, air cooled	0.39	0.45	0.81	0.026	0.049	0.11	Tensile strength, lb. per sq. in.	91 000	83 000	85 000	....	74 000	87 000	87 000	82 000	....
							Yield point, lb. per sq. in.	55 000	53 000	51 000	....	47 000	40 000	....	....	....
							Elongation, per cent	10	8.5	10	....	7	7	7	10	....
							Reduction of area, per cent	11	9	13	....	12	10.0	12.5	11.5	....
							Impact, m-kg. per sq. cm.	1	4	4.5	....	7	5.5	5.5	4.5	4.0
A Annealed, air cooled	0.18	0.76	1.10	0.030	0.029	0.10	Tensile strength, lb. per sq. in.	82 000	80 000	75 000	....	73 000	80 000	87 000	78 000	....
							Yield point, lb. per sq. in.	60 000	57 000	55 000	....	47 000	45 000	41 000	....	....
							Elongation, per cent	13.5	11.4	9.0	....	27.0	17.0	19.5	23	....
							Reduction of area, per cent	19.0	14.0	10.0	....	61.0	51.0	36.0	53	....
							Impact, m-kg. per sq. cm.	1	8.5	9.5	....	14.0	13.5	11.5	7.5	5.5
F Unannealed	0.17	1.11	1.11	0.030	0.042	0.12	Tensile strength, lb. per sq. in.	70 000	69 000	68 000	....	67 000	69 000	71 000	64 000	....
							Elongation, per cent	8	9	19	....	23	18	14	17	....
							Reduction of area, per cent	8.5	9.5	14	....	40	23	23.5	28	....
							Impact, m-kg. per sq. cm.	1	1.5	2.0	....	5	8	7.5	7	5.5
E Annealed, furnace cooled	0.18	1.30	1.22	0.046	0.040	0.13	Tensile strength, lb. per sq. in.	85 000	85 000	83 000	....	74 000	70 000	71 000	70 000	....
							Yield point, lb. per sq. in.	63 000	59 000	55 000	....	53 000	43 000	43 000	....	....
							Elongation, per cent	11	19	18.5	....	22.5	20	15	18	....
							Reduction of area, per cent	11	20.5	20.5	....	33.0	32	24	29	....
							Impact, m-kg. per sq. cm.	0.5	1.5	2.5	....	6.5	7.5	6.0	5.5	4.0

steel does not require heat treatment to bring out these beneficial properties. His recommended analysis for this steel is 0.30 to 0.35 per cent carbon, 0.60 to 0.70 per cent manganese and 0.50 to 0.60 per cent silicon. The tensile strength of such steel is 12,000 to 15,000 lb. per sq. in. higher than that of a similar but low-silicon steel, while the elongation is only about 4 to 5 per cent less.

Properties of Silicon Cast Steels at Low and Elevated Temperatures:

Schulz and Bonsmann(45) and Körber and Pomp(8) have investigated the properties of silicon cast steels at low and at elevated temperatures. The room temperature properties for the steels used by the first investigators are given in Table XVII. Körber and Pomp studied the properties of two steels of the following chemical analysis:

STEEL	CARBON, PER CENT	SILICON, PER CENT	MANGANESE, PER CENT	PHOSPHORUS, PER CENT	SULFUR, PER CENT	COPPER, PER CENT	HEAT TREATMENT[a]
No. 1.....	0.20	0.84	0.90	0.034	0.033	0.17	1705° F. (930° C.), (8) furnace cooled
No. 2.....	0.10	0.92	0.74	0.051	0.039	0.20	1670° F. (910° C.), (1) furnace cooled

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[a] Numbers in parentheses correspond to number of hours at temperature.

The properties at low and at elevated temperatures of these steels and of steels A, C, E and F investigated by Schulz and Bonsmann are given in Table XVIII.

At both low and high temperatures the low-carbon silicon cast steels are more ductile and more resistant to impact than higher carbon steels of equal strength. In the blue-brittleness temperature range the elongation and the reduction of area of the silicon steels are reduced considerably while the tensile strength is increased slightly. From the standpoint of strength properties, these steels are not superior to carbon steels in resisting high temperatures.

Silicon cast steels become brittle at low temperatures. The embrittlement of 1 per cent silicon steels occurs quite rapidly at temperatures below 200° F. (95° C.) and, according to Körber(47) the temperature at which embrittlement takes place increases as the silicon content increases, as for example, 5 per cent silicon steel embrittles at 575 to 650° F. (300 to 345° C.).

FIELDS OF APPLICATION FOR SILICON CAST STEELS

The cast silicon steels of the composition and properties given by Rys in the preceding discussion are said to be useful for cut gears, cams and eccentrics. They are tough and strong and resist wear.

Cast steels used for high magnetic induction differ little in composition from ordinary cast steel, except that they often are somewhat lower in carbon, manganese, sulfur and phosphorus and higher in silicon for higher strength. Melmoth(9), however, believes that high silicon in mild steel castings tends to produce a coarse ferritic structure with consequently lower strength or resistance to shock impact.

TABLE XIX.—PROPERTIES OF COPPER CAST STEEL (KINNEAR).

Chemical Composition, per cent			Mechanical Properties					Heat Treatment
Carbon	Copper	Manganese	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Brinell Hardness Numbers	
0.41	0.50	....	99 000	62 000	14.0	18.8	187	Normalized 1550° F. (815° C.)
			101 000	64 000	18.0	26.4	196	Normalized 1550° F. (815° C.); drawn 1000° F. (540° C.)
0.32	0.76	....	91 000	58 000	15.5	23.3	174	Normalized 1550° F. (815° C.)
			92 000	60 000	18.5	32.5	179	Normalized 1550° F. (815° C.); drawn 1000° F. (540° C.)
0.29	0.94	....	88 000	58 000	19.0	31.2	179	Normalized 1550° F. (815° C.)
			104 000	76 000	20.5	36.4	207	Normalized 1550° F. (815° C.); drawn 1000° F. (540° C.)
0.31	2.72	....	105 000	87 000	11.0	18.5	217	Normalized 1550° F. (815° C.)
			110 000	92 000	14.5	28.5	228	Normalized 1550° F. (815° C.); drawn 1000° F. (540° C.)
0.32	4.98	....	119 000	98 000	9.0	14.1	255	Normalized 1550° F. (815° C.)
			118 000	99 000	11.5	22.3	248	Normalized 1550° F. (815° C.); drawn 1000° F. (540° C.)
0.09	0.96	0.64	71 000	45 000	31.0	59.8	143	Normalized 1650° F. (900° C.)
			88 000	69 000	24.5	57.5	187	Normalized 1650° F. (900° C.); drawn 900° F. (480° C.)
0.13	1.00	0.62	70 000	50 000	31.0	54.1	143	Normalized 1600° F. (870° C.)
			89 000	70 000	23.5	49.7	196	Normalized 1600° F. (870° C.); drawn 950° F. (510° C.)
0.26	1.08	0.60	105 000	80 000	23.0	50.5	228	Normalized 1550° F. (815° C.); drawn 1000° F. (540° C.)
0.22	0.92	0.66	100 000	75 000	23.0	52.2	208	Normalized 1550° F. (815° C.); drawn 1000° F. (540° C.)
0.33	1.02	0.74	107 000	79 000	20.0	39.7	197	

COPPER CAST STEEL

Considerable development has taken place during the past few years in the use of copper in steel castings. The presence of appreciable amounts of copper above 0.5 per cent results in improved mechanical properties in steel in the as-cast or normalized condition. Still better results are secured, however, by reheating normalized castings containing more than 0.5 per cent copper to develop age-hardening by the precipitation of submicroscopic copper crystals. The discovery of the precipitation-hardening phenomenon in copper cast steels has opened up an important field of development, especially as the reheating temperature is low, 850 to 1050° F. (455 to 565° C.).

Kinnear(48), in this country, was the first to recognize and develop this precipitation-hardening action. In Table XIX are given some results taken from his work. Results are given for a number of copper cast steels in the normalized and in the normalized-and-drawn condition.

The increase in mechanical properties when the normalized steels are reheated is much greater for the low-carbon than for the higher-carbon steels. Likewise, the temperature required to produce the hardening effect is lower for the steels of lower carbon content. The yield point and tensile strength of a low-carbon copper steel can be increased about 20,000 lb. per sq. in. when reheated to 900° F. (480° C.) and allowed to cool. The increase in strength of a higher-carbon (0.25 to 0.30 per cent) copper steel is about 15,000 lb. per sq. in. when reheated to 1000° F. (540° C.). Improvement in hardness and also in elongation and reduction of area results from the reheating of copper steels that contain 0.35 to 0.40 per cent carbon.

As an alloying element, copper increases the tensile strength, the Brinell hardness, and the elastic limit and has a remarkable influence on the yield point of steels. It is noteworthy that the ratio of yield point to tensile strength for copper steels greatly surpasses the ratio for carbon steels. A copper content of from 0.90 to 1.50 per cent appears to be sufficient for the maximum tempering effect.

Mechanical Properties of Copper Cast Steel at Elevated Temperatures:

Nehl(49) has compared the properties of a copper steel to that of a carbon steel of equal strength at room and at elevated temperatures. The chemical composition of the steels studied are as follows:

	Carbon, per cent	Manganese, per cent	Silicon, per cent	Sulfur, per cent	Phosphorus, per cent	Copper, per cent
Copper steel.......	0.16	0.55	0.34	0.021	0.021	1.06
Carbon steel.......	0.38	0.65	0.39	0.021	0.038	0.15

The two steels were cast into billets of the same size. The copper steel billets were annealed at 1650° F. (900° C.) and cooled in air. Some of these were given an age-hardening treatment by heating at 930° F. (500° C.) for 1½ hours. The carbon steel was annealed at 1700° F. (925° C.). The mechanical properties of the products from these treatments are given in Table XX.

This comparison shows the superiority of the tempered copper steel over the carbon steel of equal tensile strength. It is quite evident that copper steels surpass carbon steels in their high-temperature yield point values which would indicate, though it is not proof of, better creep resistance.

Copper with Other Alloying Elements in Steel:

The effect of copper in nickel-manganese steels was mentioned in the discussion of the data for Table XV. Kinnear(48) and Buchholtz and Köster(50), in experiments on alloy cast steels, were able to obtain the same hardening effects of copper when used in combination with such alloying elements as molybdenum, chromium, vanadium and zirconium. The latter investigators found abrupt changes in the mechanical properties of a low-carbon chromium-copper steel when tempered between 850 and 1050° F. (455 and 565° C.). They likewise noted an increase in the electrical conductivity and the specific gravity of the steel when tempered over that temperature range. Developments in complex copper-bearing alloy cast steels have not reached the stage where commercial data are available. But it appears quite possible that copper steels can be improved immensely through the addition of other alloying elements and, conversely, that other alloy steels can be improved by the use of copper.

TABLE XX.—PROPERTIES OF COPPER STEEL AT ELEVATED TEMPERATURES (NEHL).

Steel	Mechanical Properties	Temperature of Test				
		68° F. (20° C.)	212° F. (100° C.)	392° F. (200° C.)	572° F. (300° C.)	752° F. (400° C.)
Copper steel, annealed	Tensile strength, lb. per sq. in	74 000	69 000	68 000	67 000	61 000
	Yield point, lb. per sq. in	51 000	48 000	45 000	36 000	34 000
	Yield ratio	68.1	69.5	66.3	53.1	56.3
	Elongation, per cent	22.5	22.1	17.3	15.3	18.0
	Reduction of area, per cent	51.2	46.4	39.5	31.0	20.5
Copper steel, annealed and drawn	Tensile strength, lb. per sq. in	88 000	81 000	83 000	80 000	66 000
	Yield point, lb. per sq. in	65 000	62 000	59 000	51 000	43 000
	Yield ratio	74.1	75.8	71.3	63.1	65.2
	Elongation, per cent	15.1	13.9	13.0	14.6	15.6
	Reduction of area, per cent	41.0	42.7	36.0	24.4	23.7
Carbon steel, annealed	Tensile strength, lb. per sq. in	87 000	80 000	80 000	85 000	72 000
	Yield point, lb. per sq. in	44 000	41 000	37 000	35 000	31 000
	Yield ratio	56.6	51.3	47.5	40.8	43.2
	Elongation, per cent	17.6	18.5	16.3	20.3	25.3
	Reduction of area, per cent	27.6	30.5	28.0	22.0	56.0

Fields of Application of Copper Cast Steel:

The tempered copper steel is suitable for use in castings that cannot be quenched in oil or water because of the danger of developing strains or cracks. A small tonnage of copper steel is now being used in the production of railway and excavating-machinery castings.

TABLE XXI.—PROPERTIES OF NICKEL CAST STEEL.

Steel	Chemical Composition, per cent						Mechanical Properties							Treatment of Steel[a]	References
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Nickel	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Impact, m-kg. per sq. cm.	Brinell Hardness Numbers		
No. 1	0.17	0.80	0.34	0.028	0.014	2.70	80 000	48 000	....	30.4	55.8	....	140 to 150	1800° F. (980° C.), furnace cooled; 1400° F. (760° C.), furnace cooled	Newman, Pascoe (52)
No. 2	0.22	0.97	0.17	....	....	0.96	84 000	54 000	....	....	....	17.0	....	1560° F. (850° C.), air cooled	Rys (44)
							85 000	64 000	....	....	....	23.0	....	1560° F. (850° C.), oil quenched	
No. 3	0.26	0.90	0.18	0.02	0.04	1.76	96 000	....	56 000	15.0	14.0	5.1	....	1475° F. (800° C.) (4), air cooled	McKnight (42)
							87 000	....	53 000	21.0	22.5	7.5	....	1475° F. (800° C.) (4), air cooled; 1290° F. (695° C.), furnace cooled	
							92 000	....	52 000	28.5	39.8	8.22	....	1475° F. (800° C.) (4), furnace cooled	
							92 000	....	53 000	33.0	52.8	9.31	....	1475° F. (800° C.) (4), furnace cooled; 1290° F. (695° C.), furnace cooled	
No. 4	0.35	0.88	0.31	0.025	0.017	1.54	103 000	61 000	....	16.0	32.5	8.4	....	1510° F. (820° C.) (4), air cooled to 1110° F. (600° C.), furnace cooled	Piwowarsky, Nipper (22)
							100 000	59 000	....	7.3	10.0	1.9	....	As cast	
No. 5	0.35	0.82	0.31	0.026	0.017	3.00	111 000	72 000	....	13.0	22.0	5.2	....	1435° F. (780° C.) (4), air cooled to 1110° F. (600° C.), furnace cooled	
							74 000	60 000	....	3.0	4.5	1.8	....	As cast	
No. 6	0.23	0.75	0.21	0.02	0.035	1.53	77 000	....	43 000	24.0	32.6	....	....	As cast	Barton (46)
							97 000	....	54 000	26.2	41.9	....	....	1500° F. (815° C.), furnace cooled	
No. 7	0.25 to 0.30	0.60 to 0.70	0.20 to 0.30	....	....	3.25 to 3.50	85 000	....	46 000	20.0	48.0	....	....	As cast	
							84 000	....	44 000	24.4	53.2	....	....	1450° F. (785° C.), furnace cooled	
							93 000	....	75 000	20.7	66.4	....	....	1400° F. (760° C.), water quenched	
							102 000	....	81 000	19.8	71.7	....	....	1400° F. (760° C.), water quenched; 900° F. (480° C.), air cooled	

[a] Numbers in parentheses correspond to number of hours at temperature.

Castings containing about 1.5 per cent copper are being used for corrosion resistance in oil refineries.

NICKEL CAST STEELS

Cast steels with nickel contents ranging from 0.5 to 5.0 per cent and with carbon from 0.10 to 0.60 per cent are among the oldest commercial alloy steels. They are characterized by high tensile strength and elastic limit, very good ductility and excellent resistance to impact. In spite of the prominence of these steels, specific information on their properties is extremely difficult to find. Some of the available data on a number of nickel cast steels are given in Table XXI.

TABLE XXII.—PROPERTIES OF NICKEL CAST STEEL AT LOW AND ELEVATED TEMPERATURES.

Steel	Mechanical Properties	Temperature of Test						
		−114° F. (−81° C.)	68° F. (20° C.)	212° F. (100° C.)	392° F. (200° C.)	572° F. (300° C.)	752° F. (400° C.)	932° F. (500° C.)
A[a]	Tensile strength, lb. per sq. in.	74 000	68 000	....	....	....	....	....
	Yield point, lb. per sq. in.	52 000	51 000	....	....	....	....	....
	Elongation in 2 in., per cent	38.25	36.75	....	....	....	....	....
	Reduction of area, per cent	65.20	66.10	....	....	....	....	....
	Izod Impact	16.6	71.6	....	....	....	....	....
B[a]	Tensile strength, lb. per sq. in.	89 000	85 000	....	....	....	....	....
	Yield point, lb. per sq. in.	54 000	50 000	....	....	....	....	....
	Elongation in 2 in., per cent	32.5	32.0	....	....	....	....	....
	Reduction of area, per cent	64.38	62.81	....	....	....	....	....
	Izod impact	4.0	33.4	....	....	....	....	....
No. 4 As cast	Tensile strength, lb. per sq. in.	....	100 000	95 000	91 000	96 000	91 000	64 000
	Elastic limit, lb. per sq. in.	....	54 000	50 000	47 000	44 000	42 000	41 000
	Elongation in 2 in., per cent	....	7.3	8.5	8.5	7.0	9	7.5
	Reduction of area, per cent	....	10.0	12.0	16.0	12.0	15.0	13.5
	Impact, m-kg. per sq. cm.	....	1.9	4.9	6.0	6.2	5.8	4.9
No. 4 Annealed	Tensile strength, lb. per sq. in.	....	103 000	95 000	92 000	100 000	91 000	60 000
	Elastic limit, lb. per sq. in.	....	61 000	57 000	50 000	46 000	41 000	39 000
	Elongation in 2 in., per cent	....	16.0	17.5	15.5	13.5	18.0	24.0
	Reduction of area, per cent	....	32.5	38.0	35.0	25.0	39.0	55.0
	Impact, m-kg. per sq. cm.	....	8.4	11.2	10.2	9.9	9.8	7.9
No. 5 As cast	Tensile strength, lb. per sq. in.	....	74 000	93 000	96 000	98 000	91 000	64 000
	Elastic limit, lb. per sq. in.	....	60 000	54 000	53 000	49 000	48 000	46 000
	Elongation in 2 in., per cent	....	3.0	4.0	7.0	5.0	7.5	6.5
	Reduction of area, per cent	....	4.5	5.2	9.5	8.0	13.0	9.0
	Impact, m-kg. per sq. cm.	....	1.8	2.1	3.3	5.1	5.1	4.2
No. 5 Annealed	Tensile strength, lb. per sq. in.	....	111 000	105 000	102 000	110 000	95 000	66 000
	Elastic limit, lb. per sq. in.	....	72 000	68 000	60 000	59 000	53 000	49 000
	Elongation in 2 in., per cent	....	13.0	13.5	12.0	11.7	15.0	17.5
	Reduction of area, per cent	....	22.0	25.0	20.0	17.0	22.5	26.0
	Impact, m-kg. per sq. cm.	....	5.2	6.8	6.9	7.1	6.0	4.2

[a] Chemical composition, per cent (Bull(18)):

	Carbon	Manganese	Sulfur	Phosphorus	Nickel
Steel A	0.10	0.69	0.034	0.010	2.48
Steel B	0.15	1.07	0.028	0.010	2.51

The presence of nickel lowers the austenite-pearlite transformation and tends to retard the changes occurring on cooling through the critical range. Some of the harder intermediate products of the transformation may be retained in air or furnace cooling with consequent improvement in both strength and ductility. The properties of a slowly cooled nickel steel are well illustrated in steel No. 3, Table XXI.

To develop high impact and fatigue resistance in a steel containing 0.20 per cent carbon (maximum), 2.0 per cent nickel (minimum), 0.60 to 0.90 per cent manganese and 0.15 per cent silicon (minimum), Zima(43) used the following treatment: Heating two hours per inch thickness at 1750° F. (955° C.) with air cooling, normalizing for $1\frac{1}{2}$ hours per inch thickness at 1500 to 1550° F. (815 to 840° C.) then drawing at 1100 to 1250° F. (595 to 675° C.) with furnace cooling. The average properties of such steel treated in this manner are:

Tensile strength, lb. per sq. in.	75 000 to 85 000
Elastic limit, lb. per sq. in.	45 000 to 55 000
Elongation, per cent	23 to 32
Reduction of area, per cent	45 to 65
Izod impact, ft-lb	60 to 80

Zima reports that by increasing the carbon content the tensile properties may be increased with a slight decrease in ductility.

Properties of Nickel Cast Steel at Low and Elevated Temperatures:

Some results of studies of the properties of nickel cast steel at low and at elevated temperatures are summarized in Table XXII. The composition, heat treatment and names of investigators of these steels were given in the preceding table, Table XXI. Steel No. 5, described by Piwowarsky and Nipper(22), contained 0.23 per cent chromium. The temperature of 1435° F. (780° C.) employed in annealing this steel in all probability was too low, so that the indication that the tensile strength and elastic limit are improved at the expense of ductility and notch toughness is, therefore, not very conclusive. The result seems to indicate, however, that the presence of nickel does not enhance the tensile properties of cast steel at high temperatures.

According to Bull(18), "Cameron found that the addition of about 1.00 per cent nickel to carbon steel, normalized or hot-worked, containing up to 0.40 per cent carbon, results in a retention, at temperatures as low as $-35°$ F. ($-37°$ C.), of the Charpy impact value at room temperature, and that 3.00 per cent nickel added to steel containing 0.80 per cent carbon increases the Charpy impact value to substantially the same extent." On the other hand, Moffatt(27) states that castings containing 2.00 to 3.00 per cent nickel exhibit approximately the same impact resistance at low temperatures as castings containing from 0.18 to 0.22 per cent vanadium. His results on plain carbon steel and on vanadium steel of the same carbon content do not differ sufficiently in their resistance to impact at low temperatures to indicate a superiority of the one steel over the other.

The impact properties of nickel steel castings show exceptionally high resistance to deterioration upon long exposures at extremely high temperatures. For example, Guillet(51) reports the following impact properties of low-carbon steel with those of a 2 per cent nickel steel of the same carbon content after these steels had been subjected to a prolonged heating above their critical temperatures:

TIME OF HEATING AT 1830° F. (1000° C.)	LOW-CARBON STEEL, KG-M.	LOW-CARBON STEEL CONTAINING 2 PER CENT NICKEL, KG-M.
Normal heating	20.0	60 (not broken)
Four hours	4.5	60 (not broken)
Six hours	4.0	60 (not broken)

Field of Application for Nickel Cast Steel:

Low-carbon nickel steels are used in many locomotive castings because of their high resistance to impact and fatigue. In addition, such castings are used for mining and excavating machinery, for marine equipment, rolling mill machinery and for bridge castings. They are sometimes used for ship screws because of their reputed resistance to sea water corrosion.

NICKEL-MOLYBDENUM CAST STEELS

Molybdenum is sometimes added to nickel steels to improve their mechanical properties at room and at high temperatures. The hardening tendencies of nickel steels are greatly augmented by small quantities of molybdenum. The best properties of nickel-molybdenum cast steels are developed by heat treatment, owing to the tendency of these steels to air harden. Unless they are tempered the normalized steels are likely to have poor impact and ductility properties. It is generally recognized that the heat-treated nickel-molybdenum steels have a slightly higher ductility and are more easily machined than many similar alloy steels of the same strength.

Very little information is available on the properties of nickel-molybdenum cast steels at room temperature. Mitchell(20) published curves showing the influence of tempering temperature on the properties of a quenched nickel-molybdenum steel but did not give its analysis. Data taken from this work are given in Table XXIII. It is unfortunate that the chemical composition of the steel is not known. These results, through their elongation and reduction of area values, illustrate the exceptional resistance to tempering of the molybdenum-containing cast steels.

TABLE XXIII.—PROPERTIES OF QUENCHED NICKEL-MOLYBDENUM CAST STEEL TEMPERED AT VARIOUS TEMPERATURES.

Tempering Temperature		Mechanical Properties				
deg. Fahr.	deg. Cent.	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Hardness Numbers
500	260	210 000	190 000	8.5	20.0	418
600	315	202 000	180 000	10.0	23.0	390
700	370	193 000	170 000	11.5	26.0	360
800	425	180 000	155 000	13.5	29.0	335
900	480	163 000	140 000	15.0	32.5	310
1000	540	150 000	122 000	16.0	36.0	285
1100	595	135 000	108 000	18.0	41.0	255
1200	650	119 000	95 000	20.0	48.0	228
1300	705	100 000	75 000	27.0	58.0	200

TABLE XXIV.—PROPERTIES OF CAST NICKEL-MOLYBDENUM STEEL AT 930° F. (500° C.).

Steel	Chemical Composition, per cent							Mechanical Properties			
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Nickel	Molybdenum	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 150 mm., per cent	Reduction of Area, per cent
No. 1	0.09	0.66	0.20	0.035	0.018	2.11	0.62	53 000	30 000	16.5	51.5
No. 2	0.18	0.97	0.21	0.042	0.013	2.10	0.56	60 000	36 000	11.0	20.5
No. 3	0.11	0.68	0.19	0.034	0.013	2.05	0.35	51 000	27 000	19.3	57.8
No. 4	0.29	0.92	0.23	0.031	0.011	2.05	0.28	61 000	38 000	12.7	31.8
No. 5	0.20	0.80	0.30	0.029	0.014	2.10	0.19	52 000	30 000	19.8	41.2
No. 6	0.21	0.68	0.18	0.042	0.014	1.62	0.51	55 000	31 000	17.1	25.3
No. 7	0.25	0.85	0.18	0.028	0.009	1.62	0.49	58 000	33 000	13.5	20.8
No. 8	0.19	0.81	0.22	0.035	0.014	1.59	0.43	49 000	30 000	14.3	23.9
No. 9	0.21	0.85	0.25	0.034	0.012	1.56	0.30	52 000	28 000	19.4	29.7
No. 10	0.20	0.81	0.29	0.030	0.014	1.58	0.23	49 000	28 000	20.6	35.3
No. 11	0.20	0.83	0.27	0.032	0.010	1.12	0.52	55 000	29 000	15.1	40.5
No. 12	0.19	0.82	0.26	0.024	0.013	1.15	0.47	54 000	28 000	16.7	44.2
No. 13	0.19	0.80	0.28	0.022	0.011	1.13	0.40	50 000	27 000	19.6	47.3
No. 14	0.21	0.80	0.30	0.018	0.014	1.13	0.33	48 000	26 000	27.0	43.0
No. 15	0.19	0.81	0.28	0.042	0.014	1.08	0.22	48 000	26 000	17.5	32.4
No. 16	0.24	0.81	0.33	0.023	0.011	0.63	0.62	55 000	29 000	23.6	33.5
No. 17	0.22	0.71	0.29	0.020	0.010	0.58	0.53	51 000	27 000	24.1	48.4
No. 18	0.17	0.83	0.30	0.030	0.013	0.62	0.39	48 000	25 000	30.0	57.2
No. 19	0.18	0.81	0.28	0.042	0.014	0.61	0.28	46 000	23 000	28.0	59.5
No. 20	0.18	0.79	0.29	0.040	0.014	0.63	0.24	42 000	23 000	29.3	59.0
No. 21	0.15	0.80	0.30	0.039	0.011	0.45	0.51	51 000	28 000	20.1	44.9
No. 22	0.25	0.81	0.31	0.023	0.014	0.43	0.45	51 000	27 000	24.7	49.1
No. 23	0.21	0.79	0.31	0.025	0.012	0.42	0.35	54 000	26 000	23.4	59.6
No. 24	0.18	0.81	0.30	0.032	0.014	0.43	0.26	47 000	24 000	23.9	41.5
No. 25	0.18	0.80	0.28	0.040	0.014	0.45	0.20	44 000	24 000	26.8	35.0

Zima(43) reported that a commercial foundry obtained the following results with steel castings containing 0.25 to 0.30 per cent carbon, 0.60 to 0.80 per cent manganese, 1.25 to 1.50 per cent nickel, and 0.30 to 0.35 per cent molybdenum:

Tensile strength, lb. per sq. in	85 000 to 90 000
Elastic limit, lb. per sq. in	55 000 to 60 000
Elongation in 2 in., per cent	22 to 25
Reduction of area, per cent	45 to 50

It is assumed that the castings were given a normalizing and drawing treatment.

Liestmann and Salzmann(53) studied the effect of molybdenum and nickel on the properties of cast steels heated to 930° F. (500° C.). Five series of alloys were prepared containing, respectively, 0.4, 0.6, 1.0, 1.5 and 2.0 per cent nickel with the molybdenum in each series varying from 0.2 to 0.6 per cent. The composition and properties of the steels are given in Table XXIV. Prior to the tests the steels were annealed at between 1650 and 1740° F. (900 and 950° C.).

Liestmann and Salzmann drew the following conclusions concerning the effects of nickel and molybdenum on cast annealed steel when heated to 930° F. (500° C.): Small additions of nickel alone have no special influence on the yield point and strength. The combined effects of nickel and molybdenum, however, raise the tensile strength and yield point but decrease the elongation and reduction of area. An increase of 0.1 per cent in molybdenum raises the yield point 1500 lb. per sq. in. and the tensile strength 3000 lb. per sq. in., while an increase of 0.5 per cent nickel raises the yield point and tensile strength 3000 and 2700 lb. per sq. in., respectively.

Fields of Application for Nickel-Molybdenum Cast Steels:

There is as yet no widespread application of the nickel-molybdenum cast steels. The increased strength properties and resistance to creep at high temperatures of molybdenum-containing steels should ultimately place the nickel-molybdenum cast steels in a position for service at high temperatures. They might also find service for case carburized parts, since such steels are easily case-carburized leaving a core of great toughness.

MOLYBDENUM CAST STEEL

The use of molybdenum cast steel possesses some distinct advantages. Molybdenum has little effect on the mechanical properties of steels that are not heat treated but it produces a substantial increase in the tensile strength of heat-treated steels containing more than 0.30 per cent carbon.

Hadfield(54) studied the properties of two series of molybdenum steels, one as cast and the other after annealing at 1470° F. (800° C.).

He concluded that molybdenum did not have a marked effect on the properties of low-carbon cast steels.

TABLE XXV.—TENSILE PROPERTIES OF CENTRIFUGALLY CAST MOLYBDENUM STEEL.

Steel	Composition, per cent		Tempering Temperature		Position in Gun	Mechanical Properties				
	Carbon	Molybdenum	deg. Fahr.	deg. Cent.		Tensile Strength, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Charpy Impact, ft-lb.
No. 1.......	0.36	0.48	1275	690	Breech	95 000	71 000	25.1	58.4	42
					Muzzle	94 000	68 000	25.1	56.35	41
No. 2.......	0.36	0.29	1200 to 1250	650 to 675	Breech	94 000	61 000	25.4	59.65	44
					Muzzle	92 000	61 000	25.5	65.5	48
No. 3.......	0.32	0.48	1275	690	Breech	89 000	63 000	27.0	68.1	42
					Muzzle	93 000	63 000	....	55.5	41
No. 4.......	0.38	0.31	1250	675	Breech	94 000	58 000	....	64.8	46
					Muzzle	92 000	60 000	28.0	61.1	50

TABLE XXVI.—PROPERTIES OF MOLYBDENUM CAST STEEL AT VARIOUS TEMPERATURES.

Steel	Composition, per cent			Mechanical Properties	Temperature of Tests							References
	Carbon	Manganese	Molybdenum		68° F. (20° C.)	212° F. (100° C.)	392° F. (200° C.)	572° F. (300° C.)	752° F. (400° C.)	932° F. (500° C.)	1112° F. (600° C.)	
No. 1...	0.22	0.59	0.32	Tensile strength, lb. per sq. in..............	65 000	63 000	81 000	76 000	60 000	46 000	....	Prömper, Pohl (56
				Yield point, lb. per sq. in.	38 000	37 000	36 000	35 000	34 000	33 000	....	
				Elongation, per cent....	21.0	12.0	12.8	18.8	18.5	17.7	....	
				Reduction of area, per cent................	43.0	38.2	37.9	42.2	58.6	63.6	....	
				Impact, m-kg. per sq. cm.	16.25	16.63	16.70	14.67	9.9	9.88	....	
No. 2...	0.19	0.60	0.33	Tensile strength, lb. per sq. in..............	70 000	....	....	....	....	57 000	....	Rys (44
				Yield point, lb. per sq. in.	43 000	....	....	....	....	21 000	....	
				Elongation, per cent....	25.5	....	....	....	....	30.0	....	
No. 3...	0.37	0.75	0.58	Tensile strength, lb. per sq. in..............	93 000	....	....	....	....	71 000	....	
				Yield point, lb. per sq. in.	44 000	....	....	....	....	38 000	....	
				Elongation, per cent....	18.0	....	....	....	....	29.6	....	
No. 4...	0.25	....	0.41	Tensile strength, lb. per sq. in..............	70 000	....	....	....	64 000	47 000	34 000	Stäger (57)
				Yield point, lb. per sq. in.	42 000	....	....	....	28 000	26 000	24 000	
				Elongation, per cent....	27.8	....	....	....	13.0	25.0	31.0	
				Impact, m-kg. per sq. cm.	5.4	....	....	....	4.8	3.5	3.8	
No. 5...	0.22	....	0.80	Tensile strength, lb. per sq. in..............	78 000	....	....	....	66 000	52 000	34 000	
				Yield point, lb. per sq. in.	47 000	....	....	....	28 000	28 000	23 000	
				Elongation, per cent....	25.0	....	....	....	20.0	20.0	44.5	
				Impact, m-kg. per sq. cm.	4.2	....	....	....	5.2	3.6	4.6	

In his work on the centrifugally casting of guns, Col. T. C. Dickson(55) of Watertown Arsenal used, among several different compositions, a few molybdenum cast steels. The usual heat treatment given the castings consisted in normalizing at 1740° F. (950° C.) for 4 hours, annealing at 1560° F. (850° C.) for 6 hours, quenching in water after 5 hours at 1560° F. (850° C.), and tempering for 6 hours at 1275° F. (690° C.). The average properties of samples taken from some of the gun castings are given in Table XXV.

The properties of steels Nos. 1 and 2 were taken from data made available through the courtesy of Colonel Dickson.[1] The Charpy values were obtained on a specially designed tension-impact test specimen using a Charpy machine. The reduced section of the round specimen was short enough that impact values rather than tensile values were measured. The energy absorbed was somewhat greater for this type of specimen than for the standard Charpy specimen. The properties of steels Nos. 3 and 4 were taken from the article by Colonel Dickson already referred to. The same type of impact specimens as described above was apparently used in the tests though no mention is made in the text.

Prömper and Pohl(56), Rys(44) and Stäger(57) published results of a few tests on molybdenum cast steels at various temperatures. Their results are summarized in Table XXVI. Steel No. 1 was annealed. Definite descriptions of the treatment given the remaining steels were not given.

One of the outstanding characteristics of molybdenum cast steel is its high yield point value at elevated temperatures. The yield point at 930° F. (500° C.) is 70 to 100 per cent higher for molybdenum steel than for unalloyed steel. This characteristic is reflected in the creep tests of Stäger. He determined the stress at which an elongation of 0.001 per cent per hour occurred between the 1000th and 2000th minute for steels Nos. 4 and 5 of Table XXVI. As this was an accelerated creep test the results should be used with caution. However, they are interesting and are as follows:

ACCELERATED CREEP TEST

TEMPERATURE		CREEP LIMIT, LB. PER SQ. IN.	
DEG. FAHR.	DEG. CENT.	STEEL NO. 4	STEEL NO. 5
570	300	27 000	27 000
750	400	9 250	10 000
1110	600	2 100	2 850

Fields of Application of Molybdenum Cast Steel:

The straight molybdenum cast steels are not in general use. They have been used in rolls, hydroelectric equipment, turbine housings and for many castings requiring high tensile properties at moderate temperatures. They can be case-carburized easily. Some centrifugally cast guns have been made from this steel, although now a small quantity of vanadium is used in the molybdenum steel used for this purpose.

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[1] Private communication from T. C. Dickson to J. L. Gregg, of Battelle Memorial Institute.

Owing to its air-hardening properties, molybdenum steel gives good results in castings which, because of their large size or intricate shape, cannot be quenched in liquid but which must have considerable hardness to resist abrasion(41).

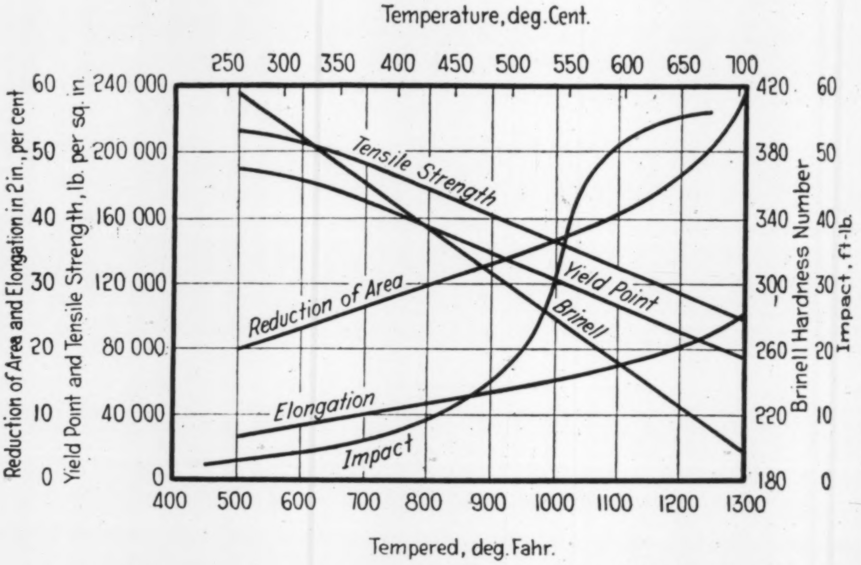

FIG. 14.—Properties of a Manganese-Molybdenum Cast Steel After Quenching in Water from 1600° F. (870° C.) and Tempering at Indicated Temperatures.

Izod specimens quenched from 1550° F. (840° C.).

MANGANESE-MOLYBDENUM CAST STEELS

Some manganese-molybdenum cast steels are made by adding 0.20 to 0.40 per cent molybdenum to the 1.0 to 1.75 per cent manganese steels of 0.30 to 0.40 per cent carbon content. The results on the whole are the same as for the nickel-manganese steels, except that the elastic ratio is said to be somewhat raised(58). A manufacturer's trade circular(59) shows the effect of tempering temperature on the properties of a steel containing 0.25 to 0.35 per cent carbon, 0.90 to 1.25 per cent manganese and 0.15 to 0.45 per cent molybdenum. These properties are shown in Fig. 14. The test specimens in the form of bars 1 in. square were heated, quenched in water, tempered and machined.

TABLE XXVII.—AVERAGE PROPERTIES OF HEAT-TREATED MANGANESE-MOLYBDENUM STEEL.

Group	Heat Treatment	Mechanical Properties					
		Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Hardness Numbers	Charpy Impact, ft-lb.
No. 1[a]..	1650° F. (900° C.), air quenched; 700° F. (370° C.), draw	134 000	101 000	15.25	44.0	292	2.25
	1650° F. (900° C.), air quenched; 1000° F. (540° C.), draw	120 000	93 000	18.0	45.4	280	8.7
	1650° F. (900° C.), air quenched; 1250° F. (675° C.), draw	96 000	68 000	25.5	57.5	210	23.0
	1575° F. (855° C.), oil quenched; 1000° F. (540° C.), draw	168 000	152 000	15.3	42.6	374	12.3
	1575 °F. (855° C.), oil quenched; 1250° F. (675° C.), draw	102 000	76 000	25.8	58.0	228	29.0
No. 2[a]..	1650° F. (900° C.), air quenched; no draw	103 650	81 750	20	43	240	9.3
	1650° F. (900° C.), air quenched; 900° F. (480° C.), draw	103 250	75 000	22	51	229	11.8
	1650° F. (900° C.), air quenched; 1275° F. (690° C.), draw	82 250	57 000	27	61	179	20.3
	1650° F. (900° C.), water quenched; 600° F. (315° C.), draw	156 000	136 000	12	40	363	3.6
	1650° F. (900° C.), water quenched; 900° F. (480° C.), draw	138 000	116 000	14	48	302	15.0
	1650° F. (900° C.), water quenched; 1000° F. (540° C.), draw	121 000	86 000	18	49	269	20.5
	1650° F. (900° C.), water quenched; 1200° F. (650° C.), draw	101 000	81 000	22	59	229	29.0
	1650° F. (900° C.), water quenched; 1300° F. (705° C.), draw	86 000	66 000	30	66	187	34.0

[a] Chemical Composition, per cent:

	Carbon	Manganese	Molybdenum	Silicon
No. 1	0.30 to 0.40	1.60 to 1.80	0.30 to 0.40	0.30 to 0.40
No. 2	0.25 to 0.35	1.25 to 1.45	0.30 to 0.40	0.30 to 0.40

TABLE XXVIII.—PROPERTIES OF CENTRIFUGALLY CAST MOLYBDENUM-VANADIUM STEEL.

Steel	Chemical Composition, per cent			Position in Casting	Tempering Temperature		Mechanical Properties				
	Carbon	Molybdenum	Vanadium		deg. Fahr.	deg. Cent.	Tensile Strength, lb. per sq. in.	Proportional Limit, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Charpy Impact, ft-lb.
No. 1	0.51	0.31	0.05	Breech	1320	715	99 000	75 000	26.7	58.3	40
				Muzzle	1320	715	101 000	73 000	25.5	57.9	43
No. 2	0.42	0.30	0.05	Breech	1290	700	99 000	73 000	25.5	57.6	40
				Muzzle	1290	700	95 000	66 000	28.9	60.7	41
No. 3	0.35	0.29	0.096	Breech	1290	700	91 000	68 000	....	51.9	39
				Muzzle	1290	700	96 000	77 000	....	60.6	36
No. 4	....	....	....	Breech	....	....	101 000	72 000	21.2	52.7	33.9
				Muzzle	....	....	97 000	70 000	24.9	57.4	36.9
No. 5	....	....	....	Muzzle	....	....	99 000	75 000	24.9	57.0	34.1
No. 6	....	....	....	Breech	....	....	93 000	67 000	19.8	37.4	28.4
				Muzzle	....	....	95 000	73 000	23.3	48.8	36.0
No. 7	....	....	....	Breech	....	....	102 000	73 000	21.2	40.8	33.5
				Muzzle	....	....	100 000	75 000	22.4	49.7	34.3
No. 8	....	....	....	Breech	....	....	97 000	72 000	22.4	49.9	35.7
				Muzzle	....	....	99 000	73 000	22.3	47.6	37.8

After being quenched from 1600° F. (870° C.) in water and tempered at 1250° F. (675° C.), this steel had an endurance limit of 53,500 lb. per sq. in., a tensile strength of 100,000 lb. per sq. in., a yield point of 75,000 lb. per sq. in., a 26 per cent elongation in 2 in. and a 60.5 per cent reduction of area.

David Zuege[1] gave the average properties of heat-treated manganese-molybdenum cast steels appearing in Table XXVII.

It will be noted from these results that the effect of a manganese content higher than that ordinarily characteristic of medium-manganese steels is to produce tensile properties, following various quenching and drawing treatments, which are extremely interesting when a given content of molybdenum is introduced into the steel. The steels containing the higher manganese percentages contain, as will be noted, a higher percentage of carbon. The results strikingly illustrate the differences in physical properties obtained by varying the temperatures for drawing.

The properties of the manganese-molybdenum steels are similar to those of the nickel-molybdenum steels, except that for a given hardness or strength their ductility is lower. Bull(18) reported creep properties of several steels as determined by J. A. Capp of the General Electric Co., among them being a manganese-molybdenum cast steel. The results based on a flow-rate of 1 per cent creep in 100,000 hours are as follows:

TYPE OF STEEL	CARBON, PER CENT	NICKEL, PER CENT	CHROMIUM, PER CENT	MOLYBDENUM, PER CENT	VANADIUM, PER CENT	MANGANESE PER CENT	SILICON, PER CENT	STRESS, LB. PER SQ. IN. 840° F. (450° C.)	930° F. (500° C.)
Nickel-chromium.	0.44	1.19	0.54	....	....	0.64	0.16	10 000	.....
Manganese-vanadium.....	0.33	....	....	....	0.26	0.97	0.29	5 900	2 500
Manganese-molybdenum..	0.33	....	....	0.30	....	0.99	0.31	15 000	12 600

The heat treatment was not reported.

These results illustrate the beneficial influence of molybdenum on creep resistance and show the superior resistance to creep at high temperatures of steels that contain molybdenum over either the nickel-chromium or the manganese-vanadium steels.

Fields of Application of Manganese-Molybdenum Cast Steel:

The manganese-molybdenum steels have a marked tendency to air harden. Unless they are heat treated properly, their ductility and toughness are poor. The properties of these steels at room temperature are so nearly equal to those of the nickel-manganese and the nickel-molybdenum steels that for many purposes the three types of steels can be used interchangeably.

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[1] Private communication from David Zuege, of the Sivyer Steel Castings Co., to J. L. Gregg, of Battelle Memorial Institute.

MOLYBDENUM-VANADIUM CAST STEEL

The adoption of molybdenum-vanadium steel for centrifugally cast guns came about after several different steel compositions were tried. See under above, "Molybdenum Cast Steel." The average properties of some of these steels are summarized in Table XXVIII. These are the typical results of tests made on specimens cut from different parts of gun castings. These data are taken from Dickson's publication(55) and from a private communication from him.

Typical heat treatment for the steels consists in normalizing at 1740° F. (950° C.) for 4 hours, annealing at 1560° F. (850° C.) for 6 hours, quenching in water after holding for 5 hours at 1560° F. (850° C.) and tempering for 6 hours at the temperatures indicated. Specially designed tension-impact test specimens were used for the Charpy tests. Chemical analyses of steels Nos. 4, 5, 6, 7 and 8 were not given but they probably were within the range of analysis finally adopted for centrifugally cast guns, which is as follows:

CARBON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT	MOLYBDENUM, PER CENT	VANADIUM, PER CENT
0.35 to 0.45	0.50 to 0.80	0.15 to 0.35	0.25 to 0.35	0.10

This steel was chosen for the centrifugally cast guns because of its excellent mechanical properties.

VANADIUM CAST STEEL

Vanadium is a deoxidizing agent and is believed to be effective in the removal of nitrogen from steel. However, most claims for the superiority of vanadium-treated steels are based on the effects of vanadium on the carbon and on the grain structure of the steel. Vanadium steel castings are notable especially for their high elastic properties, their resistance to wear, their excellent service when exposed to suddenly applied loads and their ready response to simple heat treatment.

The mechanical properties of several vanadium cast steels are given in Table XXIX.

The impact properties of vanadium cast steels in the normalized and the heat-treated conditions do not differ greatly. Thus the

TABLE XXIX.—PROPERTIES OF VANADIUM CAST STEEL.

Steel	Chemical Composition, per cent							Mechanical Properties							Treatment of Steel[a]	References
	Carbon	Manganese	Silicon	Sulfur	Phosphorus	Vanadium	Chromium	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Impact Values	Brinell Hardness Numbers		
No. 1	0.30	0.75	0.35	0.052	0.028	0.20	....	98 000	....	62 000	24	39.7	....	....	1700° F. (925° C.) $(1\frac{1}{2})$, air cooled	Barton **(46)**
								92 000	....	56 000	25	40.7	....	....	1700° F. (925° C.) $(1\frac{1}{2})$, furnace cooled	
								92 000	....	61 000	26.5	47.2	....	....	1700° F. (925° C.) $(1\frac{1}{2})$, air cooled; 1400° F. (760° C.) $(1\frac{1}{2})$, air cooled	
								89 000	....	55 000	27.5	52.0	....	....	1700° F. (925° C.) $(1\frac{1}{2})$, air cooled; 1400° F. (760° C.) $(1\frac{1}{2})$, furnace cooled	
								103 000	....	70 000	20.0	36.6	....	....	1700° F. (925° C.) (1), rapidly cooled in air	
								93 000	....	57 000	25.0	45.4	....	....	1700° F. (925° C.) (1), furnace cooled	
No. 2	0.36	0.94	0.35	0.028	0.015	0.19	....	88 000	49 000	....	28.5	53.6	....	150 to 165	1700° F. (925° C.), furnace cooled; 1200° F. (650° C.), furnace cooled	Newman, Pascoe **(52)**
No. 3	0.22	0.59	0.32	0.026	0.025	0.185	....	69 000	49 000	....	24.0	43.7	....	....	Annealed	Prömper, Pohl **(56)**
No. 4	0.24	0.52	0.24	....	....	0.60	....	99 000	67 000	....	23.0	....	3.5[b]	....	1635° F. (890° C.), air cooled	Rys **(44)**
								126 000	105 000	....	15.0	....	3[b]	....	1635° F. (890° C.), oil quenched	
No. 5	0.23	0.93	....	0.031	0.018	0.19	0.20	85 000	56 000	....	33.0	58.46	35.5[c]	....		Bull **(18)**
No. 6	0.22	1.21	....	0.021	0.049	0.20	0.28	101 000	69 000	....	24.5	50.87	21.0[c]	....		

[a] Numbers in parentheses correspond to number of hours at temperature.
[b] Values in m-kg. per sq. cm.
[c] Izod, ft-lb.

use of vanadium steel is quite advantageous for massive or intricate castings that cannot be liquid quenched.

Prömper and Pohl(56) determined the properties of the vanadium steel No. 3 of Table XXIX at elevated temperatures. The results follow:

Temperature Deg. Fahr.	Temperature Deg. Cent.	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 100 mm., per cent	Reduction of Area, per cent
68	20	69 000	49 000	24.0	43.7
212	100	67 000	43 000	19.5	45.1
392	200	71 000	42 000	16.0	34.55
572	300	67 000	34 000	28.5	51.0
752	400	66 000	33 000	26.0	53.6
932	500	42 000	25 000	36.25	67.5

These same investigators compared this vanadium steel with a plain carbon and a molybdenum cast steel of like tensile strength. At 932° F. (500° C.) the yield strength of the vanadium steel was slightly higher than that of the carbon steel but nearly 10,000 lb. per sq. in. lower than the value for the molybdenum steel.

The effects of heat treatment and of low temperature on impact properties of vanadium steel castings were studied by Moffatt(27). The composition of one of the steels studied, and which for our purposes is representative of the six steels investigated, is as follows:

Carbon, per cent	Manganese, per cent	Silicon, per cent	Sulfur, per cent	Phosphorus, per cent	Vanadium, per cent
0.25	0.64	0.27	0.062	0.033	0.19

The impact results for this steel are enumerated below:

Temperature of Test Deg. Fahr.	Temperature of Test Deg. Cent.	Izod Impact Resistance, ft-lb. per sq. in. Specimen No. 1 as Cast	Izod Impact Resistance, ft-lb. per sq. in. Specimen No. 2 1660° F. (905° C.) Furnace Cooled to 1100° F. (595° C.) Air Cooled
−40	−40	25	128
−20	−29	28	140
0	−18	30	155
20	− 7	32	172
40	4	36	190
60	16	41	215

Moffatt concluded from his work that the steel castings containing 0.18 to 0.22 per cent vanadium had as good impact resistance as castings containing 2.00 and 3.00 per cent nickel.

Bull(18) reported the following results obtained by H. B. Bowen on the properties of steels Nos. 5 and 6, Table XXIX, at −114° F. (−81° C.):

STEEL	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT	IZOD IMPACT, FT-LB.
No. 5.......	90 000	58 000	32.75	58.31	2.5
No. 6.......	108 000	72 000	24.5	47.93	2.4

Comparison of these results with those in Table XXIX for these steels at room temperature shows that the elongation and reduction of area are not greatly changed, but that resistance to impact is very low at −114° F. (−81° C.). It is to be noted that steels Nos. 5 and 6 are high in manganese and contain important amounts of chromium.

TABLE XXX.—PROPERTIES OF COMPLEX VANADIUM CAST STEEL.

Steel	Chemical Composition, per cent						Mechanical Properties					References
	Carbon	Manganese	Silicon	Nickel	Molybdenum	Vanadium	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact, ft-lb.	
No. 1....	0.22	0.85	0.35	1.50	....	0.10	83 000	61 000	29.0	59.1	60.5	Anonymous(60)
No. 2....	0.28	1.00	0.35	1.50	....	0.10	94 000	70 000	28.0	53.8	47.8	
No. 3....	0.28	1.00	0.35	1.50	....	....	94 000	54 000	27.0	56.6	35.5	
No. 4....	0.22	1.64	....	....	....	0.09	84 000	62 000	34.0	68.7	89.5	
No. 5....	0.23	1.69	....	....	....	0.09	90 000	65 000	32.0	66.0	77.5	
No. 6....	0.29	1.33	....	....	....	0.11	90 000	63 000	31.0	63.5	73.5	
No. 7....	0.29	1.38	....	....	....	0.10	93 000	70 000	30.8	61.1	61.0	
No. 8....	0.35	1.40	0.40	....	....	0.10	104 000	79 000	27.0	54.7	49.0	
No. 9....	0.35	1.50	0.40	....	0.15	0.10	119 000	74 000	23.0	39.1	30.5	
No. 10...	0.45	1.53	0.48	....	0.16	0.10	128 000	84 000	20.5	35.0	30.3	
No. 11...	0.36	1.17	0.48	....	0.33	0.10	134 000	92 000	12.0	25.4	25.5	
No. 12...	0.17	1.05	....	1.73	....	0.10	92 000	64 000	27.5	61.21	35.4	Bull (18)

Fields of Application of Vanadium Steel Castings:

Vanadium steels have given excellent service in railroad and locomotive castings. They are desirable because of their high elastic properties, their resistance to wear and impact and their ready response to simple heat treatment. The latter is very important in the development of good mechanical properties in massive and intricate castings.

PROPERTIES AND USES OF COMPLEX VANADIUM CAST STEELS

The addition of vanadium to the more complex cast steels is of material benefit. The complex vanadium cast steels are becoming increasingly popular for railway castings and for other industrial equipment where resistance to wear, tear, shock and breakdown resulting from vibration is essential. The properties of several such steels are given in Table XXX.

Steels Nos. 1 to 11, inclusive, were tested after a double normalizing treatment either with or without a subsequent tempering. The treatment for steel No. 12 was not given.

These results indicate that a substantial improvement in the elastic and impact strengths of manganese and nickel steels is obtained by the introduction of about 0.10 per cent vanadium. Hamilton(61) has shown this beneficial effect of vanadium on the medium-manganese steels in a large number of tests recently published. Hamilton(61) also compared the properties of several medium-manganese steels some of which contained 0.10 per cent vanadium. His results are given below. Analyses of the steels were not given. The specimens were given a double normalizing treatment before testing.

MECHANICAL PROPERTIES OF MEDIUM-MANGANESE STEEL

BAR	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION, PER CENT	REDUCTION OF AREA, PER CENT	IZOD IMPACT, FT-LB.
No. 1.......	108 000	70 000	26.5	55.2	20.0
No. 2.......	107 000	66 000	26.0	58.1	25.0
No. 3.......	91 000	60 000	31.0	59.6	28.0
No. 4.......	112 000	69 000	26.0	51.9	17.0
No. 5.......	107 000	65 000	25.0	52.8	16.0

Bar No. 3 contained less carbon than the others.

MECHANICAL PROPERTIES OF MANGANESE-VANADIUM STEEL

BAR	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION, PER CENT	REDUCTION OF AREA, PER CENT	IZOD IMPACT, FT-LB.
No. 1.......	107 000	80 000	26.0	54.7	46.5
No. 2.......	100 000	74 000	28.5	57.5	52.5
No. 3.......	93 000	69 000	31.0	61.1	61.0
No. 4.......	100 000	73 000	28.0	58.8	52.0
No. 5.......	101 000	76 000	27.0	56.2	53.0
No. 6.......	109 000	86 000	28.0	60.8	60.0
No. 7.......	96 000	72 000	30.5	62.3	63.0

The lower tensile strengths, particularly of steels Nos. 3 and 7, are due to lower carbon contents.

The presence of 0.10 per cent vanadium in the medium-manganese steels retards grain growth very decidedly and makes possible

TABLE XXXI.—MECHANICAL PROPERTIES OF CHROMIUM CAST STEEL.

Steel	Chemical Composition, per cent				Mechanical Properties					Treatment of Steel[b]	References
	Carbon	Manganese	Silicon	Chromium	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Brinell Hardness Numbers		
No. 1	0.35	0.67	0.37	0.77	97 000	56 000	17.5	26	207	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.), air cooled	Zuege (**38**)
No. 2	0.38	0.74	0.50	0.81	97 000	55 000	19.0	30	217	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.), air cooled	
No. 3	0.42	0.74	0.40	0.94	91 000	51 000	18.0	25.5	212	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.), air cooled	
No. 4	0.45	0.82	0.50	0.68	96 000	55 000	18.0	26.0	201	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.), air cooled	
No. 5	0.39	0.84	0.48	0.79	121 000	74 000	8.5	12.6	241	Normalized 1650° F. (900° C.), quenched; 1550° F. (840° C.), air cooled.	
					123 000	78 000	13.5	20.0	228	Normalized 1650° F. (900° C.), quenched; 1550° F. (840° C.), air cooled; 700° F. (370° C.), air cooled	
					111 000	67 000	17.0	25.0	217	Normalized 1650° F. (900° C.), quenched; 1550° F. (840° C.), air cooled; 1200° F. (650° C.), air cooled	
					194 000	156 000	3.5	3.5	418	Normalized 1650° F. (900° C.), quenched; 1550° F. (840° C.), oil quenched; 700° F. (370° C.), air cooled	
					164 000	143 000	8.5	14.1	340	Normalized 1650° F. (900° C.), quenched; 1550° F. (840° C.), oil quenched; 900° F. (480° C.), air cooled	
					120 000	90 000	16.0	35.7	241	Normalized 1650° F. (900° C.), quenched; 1550° F. (840° C.), oil quenched; 1200° F. (650° C.), air cooled	
					100 000	73 000	19.5	40.4	207	Normalized 1650° F. (900 C.), quenched; 1550° F. (840° C.), oil quenched; 1350° F. (735° C.), air cooled	
No. 6	0.49	0.70	0.40	1.10	119 000	86 000	14.1	33.0	....	Quenched 1635° F. (890° C.), oil quenched; 1110° F. (600° C.), air cooled	Rys (**44**)
No. 7	0.60 to 0.70	....	....	0.50 to 0.75	79 000	66 000[a]	34.4	66.6	....	Quenched 1500° F. (815° C.), 1300° F. (705° C.), air cooled	Barton (**46**)
					101 000	94 000[a]	20.1	60.0	....	Quenched 1500° F. (815° C.), 1050° F. (565° C.), air cooled	
					114 000	103 000[a]	14.3	54.4	....	Quenched 1500° F. (815° C.), 800° F. (425° C.), air cooled	
No. 8	0.36	0.41	0.23	3.00	147 000	110 000[a]	10.0	29.9	280	Annealed, quenched 1650° F. (900° C.), oil quenched; 1100° F. (595° C.), air cooled	Herzog[c]

[a] Reported as elastic limit.

[b] Numbers in parentheses correspond to number of hours at temperature.

[c] Private communication from G. K. Herzog, Electro Metallurgical Co., July 27, 1932.

a different ratio between the carbon and manganese. This results in steels with superior mechanical properties and freedom from manganese segregation. The erratic results said to be encountered in the simple medium-manganese steels were not found in these vanadium-treated steels.

CHROMIUM, CHROMIUM-NICKEL AND COMPLEX CHROMIUM CAST STEEL

The most abundant of all classes of alloy cast steels are the chromium, the chromium-nickel and the many complex chromium varieties. They range in composition from the low alloyed cast steels, with a fraction of a per cent of chromium, to those whose chromium content becomes a substantial and even major constituent of the product. Among the latter are the stainless steel varieties and the special heat-resisting alloys, which because of their specialized and limited application are not dealt with in this paper.

PROPERTIES OF CHROMIUM CAST STEEL

The straight chromium cast steels of low chromium content are somewhat uncommon, though as a class, these castings find use where high strength and maximum hardness together with medium ductility are desired.

Chromium confers hardness and high static strength to steel with some loss in ductility. It improves the heat resistance, the high-temperature mechanical properties and the resistance to chemical action of steels. Because of the retarding influence of chromium on the austenitic transformation, good mechanical properties can be developed in chromium cast steels by mild quenching treatments.

Ordinarily in chromium cast steels, the chromium content varies from 0.50 to 1.50 per cent, while the carbon content is varied according to the type of casting and its intended use and may range from 0.15 to as high as 1.0 per cent. The most common composition is 0.40 to 0.50 per cent carbon and 0.50 to 0.90 per cent chromium.

The mechanical properties of several chromium cast steels are given in Table XXXI.

Fields of Application of Chromium Cast Steel:

Where shock stresses are not encountered, these steels are adequate for applications requiring resistance to abrasion, high strength and moderate hardness. Steels similar in composition to No. 8 are reported to have given excellent service for wear-resistant parts on digging and dredging machinery.

TABLE XXXII.—MECHANICAL PROPERTIES OF CHROMIUM-NICKEL CAST STEEL.

Steel	Chemical Composition, per cent							Mechanical Properties						Treatment of Steel [d]	References
	Carbon	Manganese	Silicon	Chromium	Nickel	Sulfur	Phosphorus	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Impact Values	Brinell Hardness Numbers		
No. 1...	0.35	0.82	0.36	0.66	1.95	0.022	0.011	130 000	113 000	14.5	29.5	....	....	1500° F. (815° C.), water quenched; 1200° F. (650° C.), air cooled	Lorenz (**63**)
								105 000	75 000	21.0	48.3	....	....	1500° F. (815° C.), air cooled	
								106 000	93 000	23.5	52.0	37[a]	248	1500° F. (815° C.), air cooled; 1200° F. (650° C.), furnace cooled	
								106 000	92 000	23.0	52.0	....	248	1500° F. (815° C.), water quenched; 1150° F. (620° C.), furnace cooled	
								107 000	89 000	21.0	51.1	44[a]	255	1500° F. (815° C.), water quenched; 1150° F. (620° C.), water quenched	
No. 2...	0.37	0.76	0.39	0.98	1.33	....	....	104 000	66 000	22.5	42	....	222	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.), air cooled	Zuege (**38**)
No. 3...	0.40	0.77	0.56	0.85	1.50	....	....	111 000	70 000	20.5	33.5	....	235	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.), air cooled	
No. 4...	0.46	0.80	0.48	0.95	1.29	....	....	101 000	62 000	20.0	35.5	....	235	1650° F. (900° C.) (3), air cooled; 1250° F. (675° C.), air cooled	
No. 5...	0.47	0.74	0.45	0.99	1.44	....	....	174 000	150 000	2.5	4.3	....	364	1650° F. (900° C.), air cooled; 1550° F. (840° C.), air quenched	
								158 000	119 000	9	22.3	....	321	1650° F. (900° C.), air cooled; 1550° F. (840° C.), air quenched; 700° F. (370° C.), air cooled	
								118 000	88 000	18	43	....	241	1650° F. (900° C.), air cooled; 1550° F. (840° C.), air quenched; 1200° F. (650° C.), air cooled	
								202 000	173 000	6	11.1	....	487	1650° F. (900° C.), air cooled; 1550° F. (840° C.), oil quenched; 700° F. (370° C.), air cooled	
								183 000	149 000	8.5	18.4	....	387	1650° F. (900° C.), air cooled; 1550° F. (840° C.), oil quenched; 900° F. (480° C.), air cooled	
								125 000	106 000	17.5	38.8	....	269	1650° F. (900° C.), air cooled; 1550° F. (840° C.), oil quenched; 1200° F. (650° C.), air cooled	

[a] Izod, ft-lb.

[d] Numbers in parentheses correspond to number of hours at temperature.

TABLE XXXII.—*Continued.*

Steel	Chemical Composition, per cent							Mechanical Properties						Treatment of Steel[d]	References
	Carbon	Manganese	Silicon	Chromium	Nickel	Sulfur	Phosphorus	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation, per cent	Reduction of Area, per cent	Impact Values	Brinell Hardness Numbers		
No. 6...	0.40	0.84	0.42	0.63	1.72	0.032	0.011	114 000	64 000	15	24.0	6[a]	241	1500° F. (815° C.), air cooled; 1150° F. (620° C.), air cooled	Lorenz (63)
								130 000	113 000	14.5	29.5	31[a]	269	1500° F. (815° C.), water quenched; 1200° F. (650° C.), air cooled	
No. 7...	0.46	0.87	0.44	0.83	1.87	0.038	0.016	109 000	68 000	19	27.8	6[a]	241	1500° F. (815° C.), air cooled; 1200° F. (650° C.), air cooled	
								139 000	120 000	13.5	23.7	26[a]	269	1500° F. (815° C.), water quenched; 1200° F. (650° C.), air cooled	
No. 8...	0.32	....	....	1.50	1.00	....	....	100 000	76 000	22.8	62	....	....	Oil quenched and drawn	Rys (44)
No. 9...	0.28	....	....	1.60	2.16	....	....	115 000	92 000	19.7	45	....	....	Oil quenched and drawn	
No. 10..	0.28	....	....	1.50	4.00	....	....	121 000	98 000	18.0	44	....	....	Oil quenched and drawn	
No. 11..	0.33	0.65	0.16	0.65	3.19	0.017	0.026	79 000	....	1.0	....	....	302	As cast	Zsak (62)
								111 000	69 000	15	34.1	4.2[b]	217	1510° F. (820° C.) (2), furnace cooled	
								110 000	64 000	16.5	45.0	4.2[b]	217	1830° F. (1000° C.) (2), furnace cooled	
								115 000	....	4	19.8	1.6[b]	255	2100° F. (1150° C.) (2), furnace cooled	
								128 000	108 000	14.5	36.0	9.5[b]	277	1510° F. (820° C.) (2), oil quenched; 1110° F. (600° C.) (1), oil quenched	
No. 12..	0.33	0.63	0.17	0.68	3.40	0.014	0.033	108 000	70 000	7.0	7.5	....	228	1650° F. (900° C.) (2), furnace cooled	
								108 000	69 000	10.0	15.2	1.3[b]	228	1830° F. (1000° C.) (2), furnace cooled	
								124 000	105 000	14.5	32.5	5.0[b]	277	1830° F. (1000° C.) (2), furnace cooled to 1510° F. (820° C.), oil quenched; 1110° F. (600° C.), oil quenched	
No. 13..	0.51	0.71	0.39	0.87	2.85	0.051	0.045	108 000	72 000	17.5	24.8	7.85[c]	....	1550° F. (840° C.) (4), air cooled; 1250° F. (675° C.) (6), furnace cooled	Hall (64)
No. 14..	0.54	0.77	0.35	0.88	2.97	0.049	0.044	128 000	81 000	12.5	11.5	5.48[c]	....	1550° F. (840° C.) (4), air cooled; 1250° F. (675° C.) (6), furnace cooled	
No. 15..	0.60	0.67	0.33	0.92	2.81	0.040	0.041	116 000	90 000	15.0	21.7	8.82[c]	....	1550° F. (840° C.) (4), air cooled; 1250° F. (675° C.) (6), furnace cooled	
No. 16..	0.30	....	....	0.7	1.75	....	....	100 000	65 000	20.0	35.0	16 to 20[c]	200	1700 to 1750° F. (925 to 955° C.), air cooled; 1100 to 1150° F. (595 to 620° C.), air cooled	Malcolm (65)
No. 17..	0.45	0.60	....	0.80	2.75	....	....	100 000	60 000	16	26	....	219	Air quenched and drawn	Zima (43)

[a] Izod, ft-lb.

[b] Mesnager sample (French) 10 by 10 by 55 mm. Notch, 2 mm. deep, 1-mm, radius. Values in m-kg. per sq. cm.

[c] Charpy, ft-lb.

[d] Numbers in parentheses correspond to number of hours at temperature.

PROPERTIES OF CHROMIUM-NICKEL CAST STEEL

The chromium-nickel cast steels are the most widely used of all the alloy steels and represent one of the best general types of heat-treated castings. They have exceptionally high strength, elastic and ductility properties and are remarkably resistant to fatigue and abrasive wear. One of their characteristics is the high ductility associated with high yield strength values.

Their retarded austenitic transformation permits a greater hardness penetration on quenching, which insures greater uniformity of properties throughout the section of heat-treated castings. Rys(44) has studied the properties of oil-quenched chromium-nickel cast steels ranging in section from 40 to 400 mm. in thickness. He obtained the following percentage decrease in the yield strength of a 0.58 per cent carbon steel and a chromium-nickel steel containing 0.35 per cent carbon, 1.94 per cent nickel and 0.86 per cent chromium:

Thickness of Section, mm.	Carbon Steel		Chromium-Nickel Steel	
	Decrease of Yield Strength, per cent	Decrease of Ratio of Yield Strength to Tensile Strength, per cent	Decrease of Yield Strength, per cent	Decrease of Ratio of Yield Strength to Tensile Strength, per cent
40	0	0	0	0
80	12	12	4.5	2
120	20	16	9.0	10
200	25	17.5	13.5	13
400	28	18.0	18.0	14

Zsak(62) pointed out the desirability of casting chromium-nickel steels at high temperatures. Steel No. 11 of Table XXXII cast at a high temperature has for all heat treatments and for the same tensile strength much better elongation, reduction of area and impact resistance than steel No. 12, which was cast at a low temperature.

Normalized-and-drawn chromium-nickel steel castings do not show markedly better mechanical properties than some of the less costly alloy steels. Their distinct advantage arises from the greater improvement in properties possible by proper heat treatment. Zuege(38) has compared the properties of chromium-nickel steels and manganese carbon steels. He noted that the normalized-and-drawn chromium-nickel steel has slightly higher yield points and tensile strengths than the normalized manganese carbon steel, but that the ductility of the former is considerably less. Rapid quenching greatly emphasizes the hardening and strengthening effects of chromium and nickel, so that at the higher hardness values the chromium-nickel steel is superior. Heat treated, the chromium-nickel steel has greater ductility in the high Brinell hardness range. It is also capable of being hardened to a much higher Brinell value than the manganese-carbon steel.

Endurance Properties of Chromium-Nickel Cast Steel:

Because of the high strength properties of chromium-nickel cast steel, its fatigue resistance is proportionately high. Interesting data are given by Zuege(38) on the endurance properties of such a steel as affected by the heat treatment. For a steel of the following composition:

CARBON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT	CHROMIUM, PER CENT	NICKEL, PER CENT
0.48	0.70	0.45	0.80	1.24

The endurance properties after various heat treatments were as follows:

TENSILE STRENGTH, LB. PER SQ. IN.	ENDURANCE LIMIT, LB. PER SQ. IN.	ENDURANCE RATIO	HEAT TREATMENT[a]
116 000	43 000	0.37	1650° F. (900° C.) (2), air cooled; 1250° F. (675° C.) (3), air cooled.
184 000	59 000	0.32	1650° F. (900° C.) (2), air cooled; 1550° F. (840° C.) (2), oil quenched; 900° F. (480° C.), air cooled.
108 000	50 000	0.46	1650° F. (900° C.) (2), air cooled; 1550° F. (840° C.) (2), oil quenched; 1200° F. (650° C.), air cooled
103 000	40 000	0.39	1650° F. (900° C.) (2), air cooled; 1550° F. (840° C.) (2), oil quenched; 1350° F. (735° C.), air cooled

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[a] Numbers in parentheses correspond to number of hours at temperature.

Malcolm(65) has reported an endurance limit of 40,000 to 45,000 lb. per sq. in. for a normalized-and-drawn steel with 0.30 to 0.35 per cent carbon, 0.70 to 0.90 per cent chromium and 1.75 to 2.25 per cent nickel. This steel with a tensile strength of 100,000 lb. per sq. in. had an endurance ratio of 0.40 to 0.45.

The maximum endurance ratio appears in the heat-treated chromium-nickel cast steel after being drawn at 1200° F. (650° C.).

PROPERTIES OF CHROMIUM-NICKEL CAST STEEL AT ELEVATED TEMPERATURES

Chromium-nickel cast steels exhibit excellent stability and strength at high temperatures. The tensile properties at high temperatures of the cast chromium-nickel steel upon which Malcolm has given the endurance properties (see above) are shown in Fig. 15. The steel was initially air-quenched from 1700 to 1750° F. (925 to 950° C.) and drawn at 1100 to 1150° F. (595 to 620° C.).

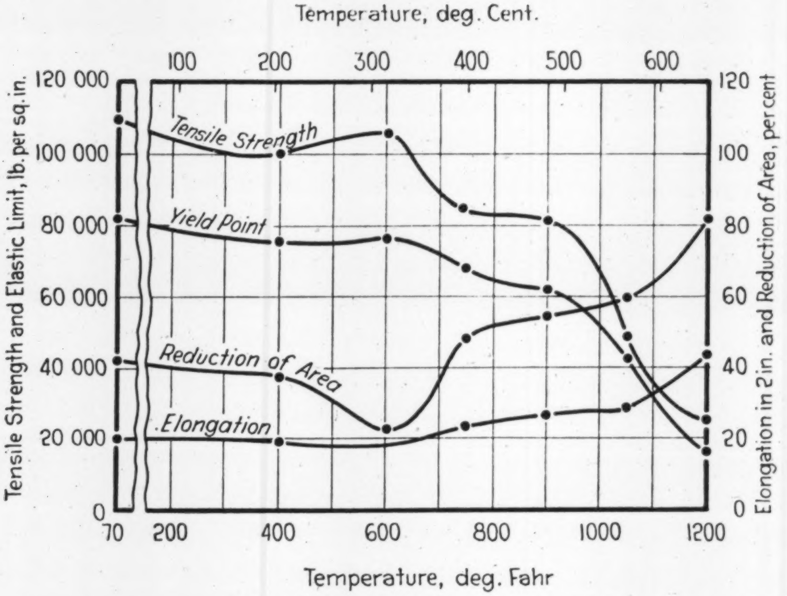

FIG. 15.—Tensile Properties of Chromium-Nickel Cast Steel at High Temperatures

Carbon, 0.30 to 0.35 per cent; chromium, 0.70 to 0.90 per cent; nickel, 1.75 to 2.25 per cent.

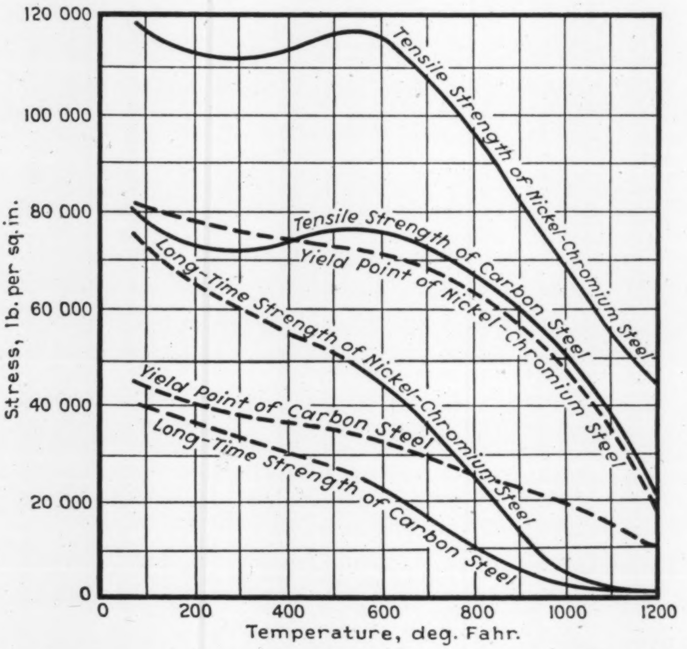

FIG. 16.—Comparison of High-Temperature Strength of Carbon and Alloy Cast Steels.

Bull(18) cited a comparison of high-temperature strength of cast carbon and chromium-nickel steels from tests made by Kanter and Spring. The steel compositions were as follows:

	CARBON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT	NICKEL, PER CENT	CHROMIUM, PER CENT
Carbon steel	0.33	0.77	0.34	....	....
Chromium-nickel steel	0.41	0.58	0.29	2.00	0.87

With the short-time tensile and yield-strength curves of Fig. 16 are given the "long-time" strength curves showing the limiting stresses producing not over one per cent of flow in a year. The dotted portion of these curves corresponds to the proportional limit values at the lower temperatures.

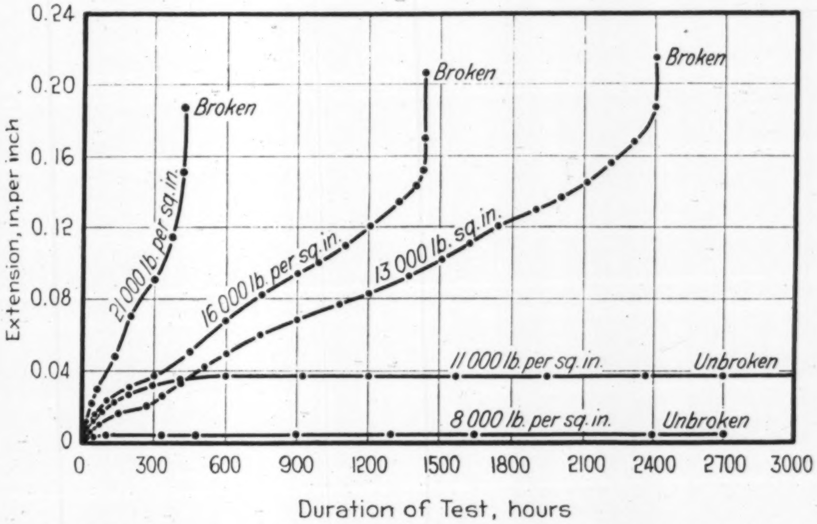

FIG. 17.—Creep Tests on Chromium-Nickel Steel at 1000° F. (540° C.).

Chromium and chromium-nickel cast steels under certain conditions exhibit what is termed "temper-brittleness," which is disclosed when impact tests are made on notched bars of the material. The brittleness occurs when the steels are heated to a temperature in the vicinity of 850 to 1025° F. (455 to 550° C.) and cooled to room temperature. Differences of 50 to 70° F. (30 to 40° C.) in the upper limit of the range were observed in steels of the same types, while temperatures as low as 600° F. (315° C.) were reported to have caused embrittlement(66). All chromium-nickel steels(67) are not made brittle by a draw from 1100° F. (595° C.) and slow cooling, though the exceptions are somewhat rare.

Greaves(68) had found that chromium-nickel steel can be made brittle by reheating to 950° F. (510° C.) whatever the subsequent rate of cooling, or by reheating to any higher tempering temperature followed by slow cooling. He found that if the critical temperature range is not exceeded, the rate of cooling after reheating is immaterial, as the steel will be brittle whether quenched or slowly cooled. Brittle steel can be restored by reheating to between 1100 and 1240° F. (595 and 670° C.) and cooling rapidly.

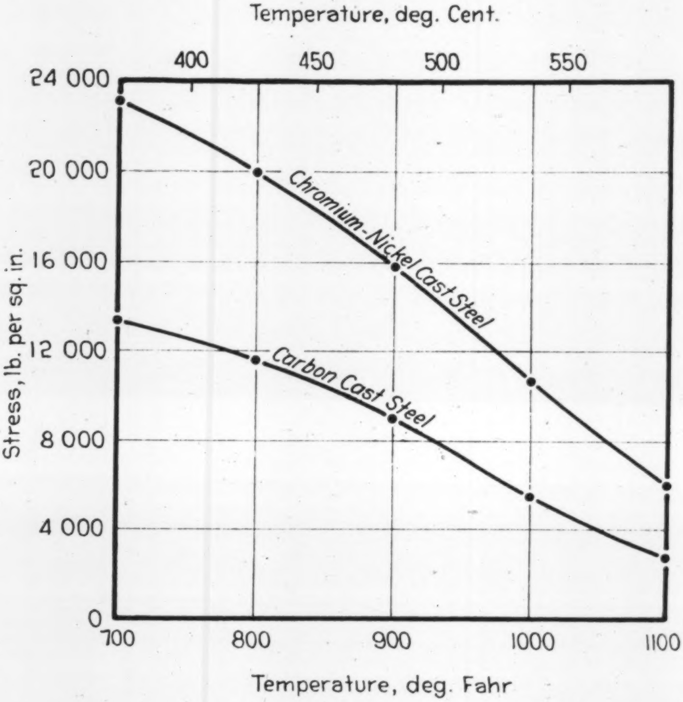

FIG. 18.—Comparison of 3 per cent Creep Limit Stresses of Chromium-Nickel and Carbon Cast Steels.

The Research Department, Woolwich(69), found that chromium and chromium-nickel steels were slightly but distinctly susceptible to temper-brittleness but that such steels containing 0.3 per cent molybdenum and over showed no signs of temper-brittleness. The effect of manganese and phosphorus to increase the susceptibility to temper-brittleness is also counteracted by the presence of molybdenum(69, 70). These investigators found that the influence of manganese is excessive when more than 0.5 per cent is present and that molybdenum greatly reduces its effect, although it does not eliminate it entirely.

No reports of impairment in tensile strength through temper-brittleness have come to the authors' attention. However, since many chromium-nickel castings are used in service at the temperatures within the embrittlement range, they are undoubtedly in an embrittled condition when they are again cooled to room temperature, thereby making them very sensitive to shock.

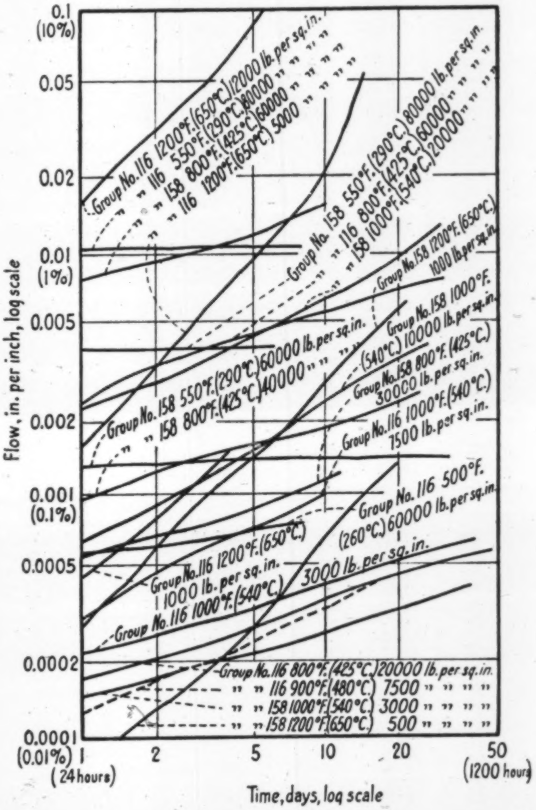

FIG. 19.—Flow-Time Curves for Heat-Treated Chromium-Nickel Cast Steel.

Creep Tests on Chromium-Nickel Cast Steel:

The creep properties of one chromium-nickel steel are given in Figs. 11, 12 and 13 under the discussion on medium-manganese cast steel.

Malcolm(65) has reported creep tests at 1000° F. (540° C.) on cast chromium-nickel steel containing 0.35 per cent carbon, 1.75 to

2.25 per cent nickel and 0.70 to 0.90 per cent chromium. His results are given in Fig. 17. The tests were conducted on steel that had been air-quenched from 1700 to 1750° F. (925 to 955° C.) followed by drawing at 1100 to 1150° F. (595 to 620° C.) Similar tests conducted for 10,000 hours indicate that the deformation under constant load of 7600 lb. per sq. in. was 2.9 per cent and that even after 26,000 hours the test specimens were still unbroken.

Figure 18, by Malcolm(65), summarizes the comparison of the chromium-nickel with a plain carbon steel. The limiting stresses, representing 3 per cent creep over a one-year period, are for steels in the air-cooled and drawn condition. These curves show that at any temperature chromium-nickel steel gives a greater factor of safety than carbon steel and also that its creep stress lies at temperatures about 100° F. (56° C.) higher than that of carbon steel.

Kanter and Spring(32) have reported the creep properties of two cast chromium-nickel steels of the following analysis:

Steel	Carbon, per cent	Manganese, per cent	Silicon, per cent	Sulfur, per cent	Phosphorus, per cent	Nickel, per cent	Chromium, per cent
Group No. 116	0.40	0.57	0.28	0.015	0.011	2.03	0.82
Group No. 158	0.41	0.58	0.29	0.010	0.017	2.00	0.87

For sake of compactness the data were plotted with logarithmic time and creep ordinates. Many of the curves of Fig. 19 take the form of straight or nearly straight lines for the entire range of flow investigated.

Fields of Application for Chromium-Nickel Cast Steel:

The chromium-nickel cast steels have very good mechanical properties. These may be obtained by a simple annealing treatment. It is preferable, however, to use the steel in the more thoroughly heat-treated state, since such treatment further enhances its mechanical properties. As they give heavier carburized cases than nickel steel, the low-carbon steels of this series are used for carburized parts. The medium-carbon chromium-nickel steels give excellent service in parts subjected to wear. Caterpillar shoes, chain belt parts, rolling mill rolls, excavating buckets, lips and teeth, and oil-well machinery are made from this steel. Some of the hardened chromium-nickel steels have replaced the Hadfield manganese alloy steels. These steels are strong at high temperature and quite resistant to corrosion. Hence they are used extensively in high-pressure vessels, containers and apparatus for chemical industries, oil refinery apparatus, fittings and valves.

PROPERTIES OF COMPLEX CHROMIUM CAST STEEL

Chromium-Manganese Silicon-Vanadium Cast Steel:

Some work has been reported to the authors on a chromium-manganese-silicon steel to which vanadium was added to obtain grain refinement. The following data[1] have been obtained with this type of steel. The chemical compositions of the three steels reported are as follows:

STEEL	CARBON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT	SULFUR, PER CENT	PHOSPHORUS, PER CENT	CHROMIUM, PER CENT	VANADIUM, PER CENT
No. 1......	0.42	1.45	0.80	0.04	0.036	0.38	0.16
No. 2......	0.32	1.14	0.68	....	.....	0.47	0.20
No. 3......	0.25	1.20	0.47	....	.....	0.52	0.17

Mechanical properties of these steels are given in Table XXXIII. Exceptionally good properties are secured by heat treatment.

Chromium-vanadium steels of normal manganese and silicon contents have been made but have not come into general use. They are characterized by their high tensile strength, good ductility and excellent resistance to fatigue.

Chromium-Molybdenum Cast Steel:

Chromium-molybdenum cast steels generally contain 0.20 to 1.00 per cent carbon, 0.70 to 1.10 per cent chromium and 0.20 to 0.40 per cent molybdenum. The molybdenum accounts for an unusually high elastic ratio with high tensile strength and good ductility.

Experiments were made at the Michigan Steel Casting Co.(71) on electric furnace steel castings of various sizes containing 0.27 per cent carbon, 0.94 per cent manganese, 1.00 per cent chromium and 0.50 per cent molybdenum. The steel was full annealed at 1650° F. (900° C.), then held 2 hours at 1575° F. (855° C.) followed by a quench, after which it was drawn at different temperatures. The mechanical properties for different drawing temperatures were given as follows:

Drawing Temperature		Mechanical Properties				
deg. Fahr.	deg. Cent.	Tensile Strength, lb. per sq. in.	Elastic Limit, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Elastic Ratio, per cent
1050	565	142 000	133 000	8.0	30.8	93.4
		154 000	142 000	10.5	28.7	91.9
1150	620	125 000	107 000	18.0	47.9	86.0
		132 000	116 000	14.0	37.3	87.6
1250	675	104 000	82 000	20.0	50.3	78.3
		110 000	89 000	20.0	43.0	80.5
1300	705	99 000	76 000	22.0	52.7	76.4
		103 000	76 000	18.5	52.8	74.1
1350	735	100 000	67 000	21.0	54.1	66.6
		99 000	66 000	21.0	51.1	66.5

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[1] Private communication from G. K. Herzog, Electro Metallurgical Co., July 27, 1932.

TABLE XXXIII.—MECHANICAL PROPERTIES OF CHROMIUM-MANGANESE SILICON-VANADIUM CAST STEEL.

Steel	Mechanical Properties				Heat Treatment [a]
	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	
No. 1......	115 000	74 000	21	41	1650° F. (900° C.) (5), oil quenched; drawn 1150° F. (620° C.)
	116 000	74 000	18.5	42.5	1650° F. (900° C.) (5), air cooled; drawn 1150° F. (620° C.)
	105 000	73 000	25.5	48.9	1650° F. (900° C.) (5), oil quenched; drawn 1450° F. (785° C.)
	108 000	62 000	20.0	47.2	1650° F. (900° C.) (5), air cooled; drawn 1450° F. (785° C.)
No. 2......	122 000	103 000	2.0	3.1	As cast
	97 000	71 000	28.0	60.3	Normalized 1650° F. (900° C.); drawn 1290° F. (695° C.)
No. 3......	109 000	78 000	5	4	As cast
	107 000	85 000	23	50	Normalized 1650° F. (900° C.); drawn 1200° F. (650° C.)

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[a] Numbers in parentheses correspond to number of hours at temperature.

TABLE XXXIV.—MECHANICAL PROPERTIES OF CHROMIUM-NICKEL-MANGANESE-MOLYBDENUM CAST STEEL.

Steel	Carbon, per cent	Mechanical Properties						Heat Treatment [a]
		Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Hardness Numbers	Charpy Impact, ft-lb.	
No. 3....	0.28	175 000	149 000	11.5	32.8	364	2.6	1650° F. (900° C.) (2), air quenched; drawn 700° F. (370° C.)
		164 000	119 000	13.5	31.2	364	7.0	1650° F. (900° C.) (2), air quenched; drawn 1000° F. (540° C.)
		119 000	89 000	22.2	51.6	255	22.7	1650° F. (900° C.) (2), air quenched; drawn 1250° F. (675° C.)
		182 000	172 000	12.7	33.3	402	10.8	1650° F. (900° C.) (2), air quenched; 1550° F. (840° C.) (2), oil quenched; drawn 1000° F. (540° C.)
		119 000	92 000	22.0	45.7	255	20.7	1650° F (900° C.) (2), air quenched; 1550° F. (840° C.) (2), oil quenched; drawn 1250° F. (675° C.)
No. 6....	0.34	240 000	175 000	9.2	29.7	477	3.1	1650° F. (900° C.) (2), air quenched; drawn 700° F. (370° C.)
		176 000	142 000	13.5	36.6	387	9.4	1650° F. (900° C.) (2), air quenched; drawn 1000° F. (540° C.)
		124 000	92 000	22.7	51.2	269	20.9	1650° F. (900° C.) (2), air quenched; drawn 1250° F. (675° C.)
		196 000	171 000	11.0	24.1	418	7.8	1650° F. (900° C.) (2), air quenched; 1550° F. (840° C.) (2), oil quenched; drawn 1000° F. (540° C.)
		126 000	98 000	19.5	45.7	269	21.1½	1650° F. (900° C.) (2), air quenched; 1550° F. (840° C.) (2), oil quenched; drawn 1250° F. (675° C.)
No. 12...	0.42	205 000	167 000	10.0	31.5	430	2.9	1650° F. (900° C.) (2), air quenched; drawn 700° F. (370° C.)
		177 000	146 000	14.5	36.2	402	7.3	1650° F. (900° C.) (2), air quenched; drawn 1000° F. (540° C.)
		119 000	91 000	19.5	42.7	269	23.5	1650° F. (900° C.) (2), air quenched; drawn 1250° F. (675° C.)
		193 000	169 000	10.7	25.3	418	7.6	1650° F. (900° C.) (2), air quenched; 1550° F. (840° C.) (2), oil quenched; drawn 1000° F. (540° C.)
		125 000	94 000	19.2	36.4	269	21.1	1650° F. (900° C.) (2), air quenched; 1550° F. (840° C.) (2), oil quenched; drawn 1250° F. (675° C.)

---

[a] Numbers in parentheses correspond to number of hours at temperature.

Best results were obtained on drawing at 1250 to 1300° F. (675 to 705° C.). The steel possessed a high reduction of area combined with unusual high tensile strength and elastic ratio. One of its advantages over the chromium-nickel steel is said to be the ease with which it can be machined(58).

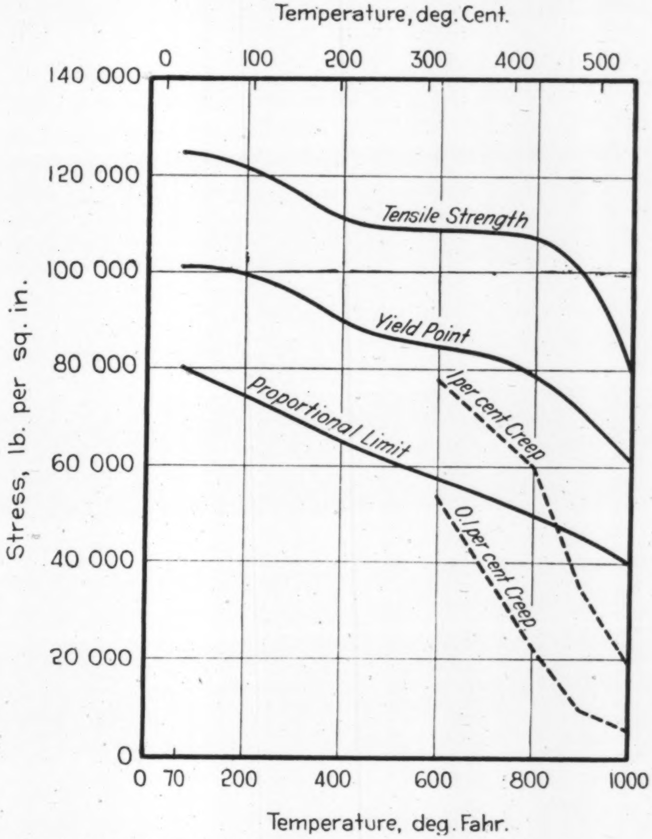

FIG. 20.—Chromium-Tungsten Cast Steel.

Short-time tension and creep tests for 0.1 and 1 per cent creep for 10,000 hours.

Chromium-Nickel-Molybdenum Cast Steel:

The addition of molybdenum to chromium-nickel steel, without reducing its good mechanical properties improves its machineability, develops air-hardening characteristics and makes the steel almost wholly immune to temper-brittleness.

Lorenz(63) has given the following general characteristics of a steel with 0.37 per cent carbon, 0.75 per cent chromium, 1.75 per cent nickel and 0.40 per cent molybdenum:

Mechanical Properties						Heat Treatment
Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Hardness Numbers	Izod Impact, ft-lb.	
162 000	130 000	3.5	3.9	450	..	Air cooled
140 000	104 000	13.0	24.4	302	6	Furnace cooled
119 000	90 000	17.0	25.1	262	27	Air cooled, drawn 1250° F. (675° C.)
101 000	60 000	17.5	33.7	212	11	Furnace cooled, drawn 1250° F. (675° C.)

This steel was extremely sensitive to changes in the rate of cooling and was not satisfactory for quenching.

A steel with 0.50 to 0.60 per cent carbon, 0.60 to 0.80 per cent manganese, 0.75 to 0.90 per cent chromium, 1.50 to 1.75 per cent nickel and 0.40 to 0.60 per cent molybdenum was described by Zima(43) to have the following mechanical properties after a normalizing treatment at 1650° F. (900° C.). The sections did not exceed 1 in. in thickness:

TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION, PER CENT	REDUCTION OF AREA, PER CENT	BRINELL HARDNESS NUMBERS
175 000 to 190 000	200 000 to 215 000	3.5 to 5.5	9.5 to 13.5	485 to 515

Toughness could only be secured by subjecting the steel to a drawing treatment after the cooling operation. Because of its sensitivity to air hardening, the steel must be carefully annealed to assure machineability.

Chromium-Nickel-Manganese-Molybdenum Cast Steel:

Zuege(38) investigated the properties of a chromium-nickel-manganese-molybdenum combination from which are selected the properties obtained on each of three heats with five different heat treatments. The analyses of the steels were as follows:

STEEL	CARBON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT	CHROMIUM, PER CENT	NICKEL, PER CENT	MOLYBDENUM, PER CENT
No. 3.........	0.28	1.56	0.41	0.68	1.18	0.36
No. 6........	0.34	1.58	0.40	0.71	1.22	0.32
No. 12........	0.42	1.48	0.34	0.60	1.26	0.39

The mechanical properties given in Table XXXIV are in each case the average of two tests.

When normalized at 1650° F. (900° C.) and drawn at a suitable temperature, the molybdenum-containing steel has markedly better all-around properties than either the plain medium-manganese or the chromium-nickel steels. Its superiority is greatest in yield point and impact values. It has exceptionally good air-hardening properties. An air-quench and draw treatment developed properties equal to and in many instances superior to those obtained by a liquid quench of the other types of steel. It has great hardening possibilities, and for a definite high hardness value has greater toughness and ductility than the chromium-nickel steel.

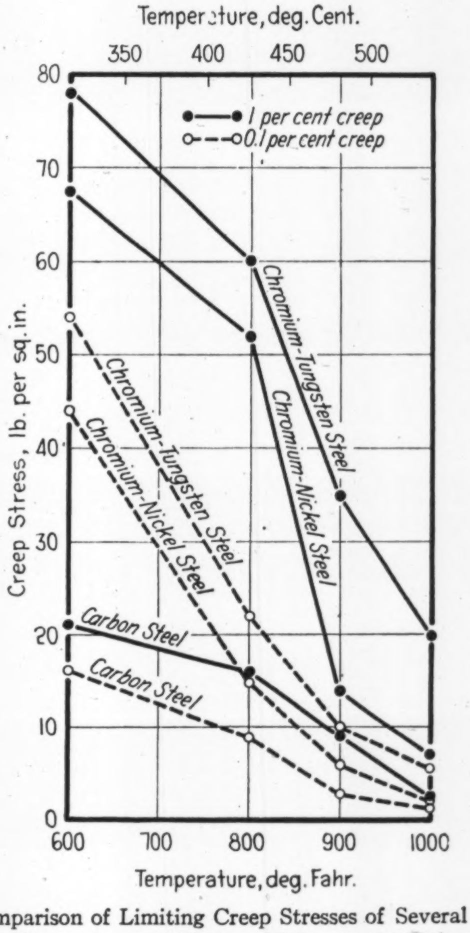

FIG. 21.—Comparison of Limiting Creep Stresses of Several Cast Steels at Various Temperatures with 1 and 0.1 per cent Deformation.

Creep stress based on 10,000-hour test.

Chromium-Tungsten Cast Steel:

Studies by Malcolm(72) of corrosion resistance and properties at elevated temperatures of metals for oil-refinery service have led to the development, for this purpose, of a chromium-tungsten cast steel containing 0.15 to 0.25 per cent carbon, 4.50 to 6.50 per cent chromium and 0.75 to 1.00 per cent tungsten. Malcolm reported an extensive study of the properties of a cast steel having the following chemical composition:

CARBON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT	SULFUR, PER CENT	PHOSPHORUS, PER CENT	CHROMIUM, PER CENT	TUNGSTEN, PER CENT
0.25	0.53	0.42	0.017	0.021	5.87	0.80

It was determined that a normalizing treatment at 1750° F. (955° C.) followed by drawing at 1200 to 1250° F. (650 to 675° C.) and furnace cooling gave the best mechanical properties and structure for stability at the temperature of service. The following properties were developed by such treatment:

Tensile strength, lb. per sq. in.	125 000
Yield point, lb. per sq. in.	100 000
Elongation in 2 in., per cent	18
Reduction of area, per cent	45
Brinell hardness number	240 to 260
Charpy impact, ft-lb	19
Endurance ratio	0.43

Short-time tension tests and limiting creep stresses at elevated temperatures for this steel are shown in Fig. 20.

Data for the limiting creep stresses of cast chromium-tungsten steel, cast chromium-nickel steel and cast carbon steel at various temperatures with 1 per cent and 0.1 per cent deformation based on 10,000-hour tests are plotted in Fig. 21. The chromium-nickel steel contained 0.35 per cent carbon, 0.80 per cent chromium and 2.00 per cent nickel. The carbon steel contained 0.35 per cent carbon. In resistance to creep the chromium-tungsten steel is much superior to the others.

Chromium-tungsten cast steels of somewhat different analyses have been used for rolls in Pilger mills for some time. Steel for this purpose contains 0.40 to 0.50 per cent carbon, 1.8 to 2.0 per cent chromium and 1.2 to 1.5 per cent tungsten(73). This steel, when heat treated, develops a tensile strength of 115,000 to 170,000 lb. per sq. in. with an elongation of 8 to 12 per cent.

REFERENCES

(1) Fred Grotts, "Representative Properties of Cast Medium Pearlitic Steels," see p. 197.

(2) Jerome Strauss, "Castings of Corrosion-Resistant Steels," see p. 213.

(3) John Howe Hall, "Austenitic Manganese Steel Castings," see p. 238.

(4) R. A. Bull, "Chemical Composition as Employed for Classifying Carbon and Alloy Steels for Castings," *Transactions*, Am. Foundrymen's Assn., Vol. 2, No. 9, p. 257 (1931).

(5) Federico Giolitti, "Steel Castings of High Strength and Toughness," *Chemical and Metallurgical Engineering*, Vol. 24, pp. 113, 161 (1921). "Heat Treatment of Soft and Medium Steels," McGraw Hill Book Co., Inc., New York City (1921).

(6) Discussion by L. Scharlibbe of paper by F. Körber, "Einfluss der Temperatur auf die Festigkeitseigenschaften von Stahlguss," *Stahl und Eisen*, Vol. 44, p. 1765 (1924).

(7) P. Oberhoffer, "Die Bedeutung des Glühens von Stahl formguss," *Stahl und Eisen*, Vol. 35, pp. 93, 212 (1915).

(8) F. Körber and A. Pomp, "Mechanische Eigenschaften von Stahlguss bei erhöhten Temperaturen," *Mitteilungen*, Kaiser-Wilhelm Institut für Eisenforschung, Vol. 10, p. 91 (1928).

(9) F. A. Melmoth, "Variables in Steel Foundry Practice," *Transactions*, Am. Foundrymen's Assn., Vol. 36, p. 323 (1928).

(10) Fred Grotts, "Broadening the Fields for Steel Castings Through the Use of Alloys and Heat Treatment," *Transactions*, Am. Foundrymen's Assn., Vol. 32, Part 1, p. 730 (1924).

(11) John Howe Hall, A. E. Nissen and K. Taylor, "Heat Treatment of Cast Steel," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 62, p. 353 (1920).

(12) A. Thum and H. Holdt, "Die Dauerstandfestigkeit von Stahlguss bei erhöhten Temperaturen," *Die Giesserei*, Vol. 17, p. 333 (1930).

(13) F. Körber and A. Dreyer, "Über Blaubrüchigkeit und Altern des Eisens," *Mitteilungen*, Kaiser-Wilhelm Institut für Eisenforschung, Vol. 2, p. 59 (1921).

(14) T. D. Yensen, "Magnetic Materials in the Year 1931," *Year Book*, Am. Iron and Steel Inst., p. 452 (1931).

(15) H. F. Moore, "Tests of the Fatigue Strength of Cast Steel," *Bulletin 156*, University of Illinois Engineering Experiment Station (1926).

(16) F. Körber and A. Pomp, "Festigkeiteigenschaften von Stahlguss bei erhöhter Temperatur," *Mitteilungen*, Kaiser-Wilhelm Institut für Eisenforschung, Vol. 6, p. 21 (1925).

(17) R. C. Allen, "Steam Turbine Materials for High Temperatures," Symposium on Effect of Temperature on the Properties of Metals, published jointly by the American Society for Testing Materials and The American Society of Mechanical Engineers, p. 30 (1931).

(18) R. A. Bull, "The Performance of Cast Iron and Low-Alloy Steels in High- and Low-Temperature Service," Symposium on Effect of Temperature on the Properties of Metals, published jointly by the American Society for Testing Materials and The American Society of Mechanical Engineers, p. 394 (1931).

(19) L. R. Mann, "Making Steel Castings Tough as Forgings," *The Iron Age*, Vol. 126, p. 425 (1923).

(20) H. A. Mitchell, "Getting the Most out of Steel Castings," *The Iron Age*, Vol. 126, p. 914 (1930).

(21) F. C. Langenberg, "Impact Tests on Cast Steel," *Proceedings*, Am. Soc. Testing Mats., Vol. 21, p. 840 (1921).

(22) E. Piwowarsky and H. Nipper, "Festigkeiteigenschaften von Stahlguss bei höheren Temperaturen unter besonderer Berüchsichtigung des Einflusses von Nickel," *Die Giesserei*, Vol. 17, p. 329 (1930).

(23) L. W. Spring, "Some Considerations and Tests for Materials for High-Temperature High-Pressure Service," *Transactions*, Am. Foundrymen's Assn., Vol. 2, No. 10, October, 1931, p. 13.

(24) K. H. Müller and E. Piwowarsky, "Warmfestigkeit von legiertem und unlegiertem Stahlguss," *Archiv für das Eisenhüttenwesen*, Vol. 5, p. 483 (1932).

(25) L. Schmid, "Der Stahlguss als Baustoff für Elektromaschinen," *Giesserei-Zeitung*, Vol. 27, p. 375 (1930).

(26) L. Schmid, "Die Verwendung von Gusseisen und Stahlguss in Elektromaschinenbau," *Die Giesserei*, Vol. 14, pp. 750, 770 (1927).

(27) R. W. Moffatt, "Effect of Low Temperature upon the Impact Resistance of Steel Castings," *Canadian Journal of Research*, Vol. 2, p. 327 (1930).

(28) F. C. Langenberg, "The Behavior of Certain Steels Under Impact at Different Temperatures," *Carnegie Scholarship Memoirs*, Iron and Steel Inst., Vol. 12, p. 75 (1923).

(29) F. Körber and A. Pomp, "Einfluss der Vorbehandlung auf die Mechanischen Eigenschaften von Kohlenstoff und legiertem Stahl, insbesondere die Kerbzähigkeit in der Kälte und Wärme," *Mitteilungen*, Kaiser-Wilhelm Institut für Eisenforschung, Vol. 7, p. 43 (1925).

(30) J. J. Kanter and L. W. Spring, "Some Long-Time Tension Tests of Steel at Elevated Temperatures," *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part I, p. 131 (1930).

(31) R. W. Bailey and A. M. Roberts, "Testing of Materials for Service in High-Temperature Steam Plant," *Engineering*, Vol. 133, pp. 261, 295 (1932).

(32) J. J. Kanter and L. W. Spring, "Long-Time or 'Flow' Tests of Carbon Steels at Various Temperatures with Particular Reference to Stresses Below the Proportional Limit," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 80 (1928).

(33) N. L. Mochel, "Thermal Expansion of Metals," Symposium on Effect of Temperature on the Properties of Metals, published jointly by the American Society for Testing Materials and The American Society of Mechanical Engineers, p. 683 (1931).

(34) J. D. Fenstermacher, "Improvements in Physical Properties in Large Carbon and Alloy Castings," *The Steel Founder*, June–July (1931).

(35) A. Oehler, "Der Stahlguss als Baustoff," *Report No. 36*, Schweizer Verband für die Materialprüfung der Technik, Eidgenossiche Materialprüfungsanstalt, December, 1929.

(36) F. A. Melmoth, "Some Metallurgical Points on Acid Open-Hearth and Electric Steel for Castings," *Transactions*, Am. Foundrymen's Assn., Vol. 2, No. 11, p. 458 (1931).

(37) John Howe Hall, "High Manganese Steel Castings," *The Iron Age*, Vol. 116, p. 879 (1925).

(38) David Zuege, "Alloy Cast Steels," *Transactions*, Am. Foundrymen's Assn., Vol. 37, p. 361 (1929).

(39) John Howe Hall, "Pearlitic and Sorbitic Manganese Steels," *The Iron Age*, Vol. 110, p. 786 (1922).

(40) Discussion by A. W. Lorenz of paper by David Zuege, "Alloy Cast Steels," *Transactions*, Am. Foundrymen's Assn., Vol. 37, p. 361 (1929). Discussion, p. 630.

(41) David Zuege, "Status of Alloy Steel Castings," *The Iron Age*, Vol. 125, p. 1294 (1930).

(42) C. McKnight, Jr., "Making Steel Castings Stronger," *The Iron Age*, Vol. 115, pp. 469, 555 (1925).

(43) A. G. Zima, "Nickel Alloy Steel Castings," *The Steel Founder*, Vol. 2, pp. 6, 23 (1932).

(44) Albert Rys, "Stahlguss in Theorie und Praxis," *Stahl und Eisen*, Vol. 50, p. 423 (1930).

(45) E. H. Schulz and F. Bonsmann, "Über die Eigenschaften von silizium-legiertem Stahl in Form von Stahlguss," *Stahl und Eisen*, Vol. 50, p. 161 (1930).

(46) L. J. Barton, "Refining Metals Electrically," Penton Publishing Co., Cleveland (1926).

(47) F. Körber, "Der Zusammenhang zwischen Kerbzähigkeit und Gleitebenenbildung," *Stahl und Eisen*, Vol. 45, p. 1146 (1925).

(48) H. B. Kinnear, "One per cent Copper Steel Has Many Desirable Physical Qualities," *The Iron Age*, Vol. 128, pp. 696, 820 (1931).

(49) F. Nehl, "Über die Mechanischen Eigenschaften kupferlegierter Stähle unter besonderer Berüchsichtigung der Wärmebehandlung," *Stahl und Eisen*, Vol. 50, p. 678 (1930). English translation in *Heat Treating and Forging*, Vol. 17, pp. 148, 252 (1931).

(50) H. Buchholtz and W. Köster, "Über die Anlasshärtung kupferlegierten Stahles," *Stahl und Eisen*, Vol. 50, p. 687 (1930).

(51) M. L. Guillet, "Traitments Thermiques des Aciers Speciaux," *Revue de Metallurgie*, Vol. 7, p. 489 (1910).

(52) W. A. Newman and C. F. Pascoe, "Making Locomotives Stronger," *The Iron Age*, Vol. 119, p. 701 (1927).

(53) W. Liestmann and C. Salzmann, "Über die Warmfestigkeit von Stahlguss mit geringen Zusätzen von Nickel und Molybdän," *Stahl und Eisen*, Vol. 50, p. 442 (1930).

(54) R. A. Hadfield, "Addendum on Alloys of Iron and Molybdenum," *Proceedings*, Inst. Mechanical Engrs., p. 701 (1915).

(55) T. C. Dickson, "Casting Guns by the Centrifugal Process," *Transactions*, Am. Soc. Steel Treating, Vol. 18, p. 212 (1930).

(56) P. Prömper and E. Pohl, "Kessel- und Behälter-baustoffe mit gesteigerter Widerstandsfähigkeit bei hohen Betriebstemperaturen," *Archiv für das Eisenhüttenwesen*, Vol. 1, p. 785 (1928).

(57) H. Stäger, "Verhalten von metallischen Werkstoffen bei hohen Temperaturen," *First Communications*, New Internat. Assn. Testing Mats., Group A, p. 89 (1930).

(58) J. W. Frank, "General Characteristics of Alloy Steel Castings," *Transactions*, Am. Foundrymen's Assn., Vol. 36, p. 119 (1928).

(59) The Bonney Floyd Co.

(60) Anonymous, "Vanadium in Steel Castings," *Foundry Trade Journal*, Vol. 45, p. 364 (1931).

(61) W. C. Hamilton, "Addition of Vanadium Improves Properties of Medium Manganese Steels," *The Iron Age*, Vol. 129, p. 546 (1932).

(62) Viktor Zsak, "Über hochwertigen Chrom-Nickel-Stahlguss," *Die Giesserei*, Vol. 16, p. 193 (1929).

(63) A. W. Lorenz, "Heat Treatment of Alloy Steel Castings," *Transactions*, Am. Foundrymen's Assn., Vol. 31, p. 193 (1924).

(64) John Howe Hall, "Manganese in Cast Steels," *Transactions*, Am. Foundrymen's Assn., Vol. 34, p. 1152 (1926).

(65) V. T. Malcolm, "Nickel-Chromium Steels for High Temperature Service —Valves and Bolts," *Bulletin No. 15*, Nickel Steel, The International Nickel Co.

(66) J. Humfrey, Discussion of Temper-Brittleness Papers, *Journal*, Iron and Steel Inst., Vol. 100, p. 377 (1919).

(67) J. Dickenson, Discussion of Temper-Brittleness Papers, *Journal*, Iron and Steel Inst., Vol. 100, p. 377 (1919).

(68) R. H. Greaves, "Temper-Brittleness of Nickel-Chromium Steel," *Journal*, Iron and Steel Inst., Vol. 100, p. 329 (1919).

(69) The Influence of Molybdenum on Medium Carbon Steels Containing Nickel and Chromium, *Report No. 67*, Research Department, Woolwich (1928).

(70) R. H. Greaves and J. A. Jones, "Temper-Brittleness of Steel. Susceptibility to Temper-Brittleness in Relation to Chemical Composition," *Journal*, Iron and Steel Inst., Vol. 111, p. 231 (1925).

(71) Anonymous, "Heat-Treated Steel Castings of Chromium-Molybdenum Steel," *The Iron Age*, Vol. 107, p. 1052 (1921).

(72) V. T. Malcolm, "A New Development of Chromium Tungsten Steel for Oil Refinery Service," reprinted in Bulletin "Cro-Tung," Industrial Steels, Inc.

(73) R. Krieger, "Die Entwicklung der deutschen Stahlformguss-Industrie in den letzten 25 Jahren," *Stahl und Eisen*, Vol. 46, p. 865 (1926).

REPRESENTATIVE PROPERTIES OF CAST MEDIUM PEARLITIC STEELS

BY FRED GROTTS[1]

The pearlitic series of steels are those composed principally of pearlite when in the normalized condition. As a rule the carbon is kept between the limits of 0.25 and 0.45 per cent, the alloying material being of such a nature as to eliminate the possibility of classifying the steel as being in a special pearlitic class. In the latter class one might place steels of analyses such as 0.25 to 0.35 per cent carbon, 2.00 to 2.25 per cent manganese, 0.40 to 0.60 per cent nickel, 0.20 to 0.30 per cent molybdenum; or 0.35 to 0.45 per cent carbon, 2.00 to 2.25 per cent nickel, 1.00 to 1.25 per cent chromium, and 0.30 to 0.40 per cent molybdenum. These two steels are pearlitic, but it is not contemplated that the author should discuss steels of such special composition, in presenting data on the medium pearlitic steels.

Pearlitic steels, as a rule, contain a small amount of a special element which may be dissolved in the ferrite, as nickel or silicon; or which may be combined with carbon as cementite, as a double carbide of iron and the special element; or which may be partially in solution in the ferrite, as manganese, chromium, tungsten, vanadium, or molybdenum.

The structure of pearlitic steels of alloyed nature might be said to be slightly different from pearlitic carbon steels, in that the pearlitic particles are more angular than in the case of carbon steel. There seems to be a finer condition of the pearlite also, when a special element is present.

Compared with carbon steel, the pearlitic steels have higher yield points and ductilities, together with greater hardness. These added properties make this series of steel especially attractive wherever it is desirable to reduce the weight of a design without lowering its strength. Again, it is sometimes desirable to increase the hardness and not sacrifice the elongation. The data submitted in this paper show that the resistance to shock is much greater in the medium pearlitic steels than in simple carbon steel.

The results given in this paper were contributed by foundries regularly producing the steels described, and were not obtained from heats made for experimental purposes. In general, a large number of heats of the different steels were studied to note their uniformity and adherence to the specified analysis. The physical properties and, where possible, the microscopic characteristics are indicated for reference and contrast. Study of the micrographs may result in differences of opinion as to whether a steel is strictly pearlitic and whether it should have been included in a paper relating to pearlitic steel castings. However, the main thought has been to collect and tabulate data on the various steels made in regular production, corresponding to this nomenclature.

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The test specimens from which the results were obtained, in some cases were taken from separate blocks, and in other cases from blocks attached to the commercial casting.

PEARLITIC CARBON STEELS

Carbon Steels, 0.40 to 0.50 per cent Carbon:

The general application of the 0.40 to 0.50 per cent carbon steels is in such castings as require added strength and abrasive properties not possessed by the low-carbon steels (0.25 to 0.35 per cent carbon), also where it is not deemed advisable to utilize a special element with less carbon. These steels are used for wheels, rails, cutting tools, gears, rolls, tractor shoes, dies, sowblocks. Quenching in oil or water followed by drawing gives desirable properties. It may be mentioned in passing that low-carbon steels (0.25 to 0.35 per cent carbon) after being quenched and drawn, give properties comparable to those in some pearlitic steels, when the latter are full-annealed only, as shown in the following table:

Material	Treatment	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
Low-carbon steel (0.34 per cent carbon, 0.80 per cent manganese, 0.32 per cent silicon, 0.39 per cent sulfur, 0.038 per cent phosphorus)	Full-annealed	83 000	39 500	27	40.0
	Quenched in oil and drawn	100 600	57 400	23	49.5
Medium-carbon steel (0.40 to 0.50 per cent carbon)	Full-annealedand normalized (Fig. 1)	84 000	47 000	19	30
High-carbon steel (0.80 to 0.90 per cent carbon)	Full-annealedand normalized (Fig. 2)	105 000	56 000	16	28

PEARLITIC LOW-ALLOY STEELS

0.30 to 0.40 per cent Carbon, 0.30 to 0.40 per cent Molybdenum:

The addition of molybdenum has a distinct effect on the yield point and toughness. It also reduces the tendency to creep at the higher temperatures. It is, therefore, of value in castings that must retain their physical properties when utilized in parts such as steam valves and in distillation work, also for tongs and hooks for lifting hot materials. Cast rolls and dies are improved by using small amounts of this element. Experience of the author indicates that one point of molybdenum has the same effect as three to four points of tungsten. A complete pearlitic or eutectoid steel results when 0.70 to 0.80 per cent molybdenum is added to a normal 0.30 to 0.45 per cent carbon steel. See Table I and Fig. 3.

TABLE I.—0.30 TO 0.40 PER CENT CARBON, 0.30 TO 0.40 PER CENT MOLYBDENUM (FIG. 3).

Heat treatment: full annealed, normalized, and drawn.

Chemical Analysis, per cent						Physical Properties						
Carbon	Manganese	Silicon	Phosphorus	Sulfur	Molybdenum	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Type of Fracture	Izod Impact Value	Brinell Hardness
0.32	0.68	0.22	0.040	0.045	0.31	75 500	62 000	23	31.4	½ cup	27	200
0.40	0.93	0.38	0.040	0.045	0.36	102 500	78 000	18	20.5	¼ cup	31	210
0.36	0.60	0.23	0.040	0.035	0.39	84 500	44 500	24	35.0	¼ cup	25	205
0.35	0.64	0.30	0.032	0.040	0.34	78 200	54 200	20	38.0	½ cup	34	220
0.33	0.70	0.31	0.038	0.035	0.30	76 000	52 000	21	40.0	½ cup	23	208
						AVERAGE						
0.35	0.71	0.29	0.038	0 040	0.34	83 200	58 100	21	33.0	......	28	208

TABLE II.—0.30 TO 0.40 PER CENT CARBON, 0.10 TO 0.20 PER CENT VANADIUM.

Heat treatment: normalized, and drawn.

Chemical Analysis, per cent						Physical Properties				
Carbon	Manganese	Silicon	Phosphorus	Sulfur	Vanadium	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value
0.384	0.87	0.32	0.033	0.036	0.195	94 100	64 900	24.0	53.9	30
0.384	0.94	0.30	0.035	0.031	0.170	93 800	59 900	23.5	46.3	29
0.334	0.88	0.33	0.030	0.037	0.195	84 800	52 100	27.0	55.7	35
0.374	0.86	0.33	0.037	0.030	0.195	94 600	59 900	24.5	46.0	32
0.410	0.96	0.32	.....	.....	0.180	91 900	57 400	26.0	51.0	33
				AVERAGE						
0.380	0.91	0.32	0.034	0.033	0.185	91 500	58 500	25.5	50.5	32

0.30 to 0.40 per cent Carbon, 0.10 to 0.20 per cent Vanadium:

A small percentage of vanadium refines the grain and generally increases all the physical properties. An interesting illustration of the effect of vanadium can be seen when the impact value of the simple pearlitic manganese steel is contrasted with the impact value of steel having a similar analysis, to which vanadium is added. This is shown in Table II.

0.30 to 0.40 per cent Carbon, 0.75 to 1.00 per cent Chromium:

Chromium increases the hardness, tensile strength, and yield point, but at the expense of some of the ductility. It increases the depth of hardness after quenching. Castings subject to abrasion, to water corrosion, or to high operating temperatures give much better service by additions of chromium. See Table III.

TABLE III.—0.30 TO 0.40 PER CENT CARBON, 0.75 TO 1.00 PER CENT CHROMIUM.

Heat treatment: air cooled from 1650° F. (900° C.), then drawn at 1250° F. (675° C.).

Chemical Analysis, per cent				Physical Properties					
Carbon	Manganese	Silicon	Chromium	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value	Brinell Hardness
0.37	0.73	0.47	0.80	96 000	53 540	18	31	28	215
0.35	0.70	0.36	0.76	94 000	52 500	19	34	30	205
0.39	0.76	0.38	0.88	99 500	58 400	16	29	26	220
0.33	0.74	0.43	0.79	92 600	51 000	20	32	32	202
0.36	0.80	0.40	0.90	97 400	60 000	17	30	28	223
				AVERAGE					
0.36	0.74	0.41	0.83	95 000	55 000	18	31	29	213

TABLE IV.—0.35 PER CENT CARBON, 0.75 PER CENT CHROMIUM, 1.50 PER CENT NICKEL (FIG. 4).

Heat treatment: full annealed at 1700° F. (925° C.), air cooled from 1650° F. (900° C.), then drawn at 1250° F. (675° C.).

Chemical Analysis, per cent					Physical Properties					
Carbon	Manganese	Silicon	Chromium	Nickel	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value	Brinell Hardness
0.35	0.80	0.40	0.94	1.30	102 000	67 400	21.0	41	38	222
0.39	0.76	0.46	0.87	1.46	108 500	69 000	19.0	37	30	228
0.37	0.84	0.42	0.92	1.35	104 000	65 300	20.0	38	32	217
0.33	0.75	0.39	0.85	1.50	99 000	60 000	22.5	45	41	212
0.40	0.79	0.38	0.89	1.30	105 200	66 000	18.5	36	26	228
					AVERAGE					
0.37	0.79	0.41	0.89	1.38	103 000	66 000	20.0	39	37	221

TABLE V.—SOME SPECIAL NICKEL STEELS.

Chemical Analysis, per cent					Treatment	Physical Properties				
Carbon	Manganese	Chromium	Nickel	Molybdenum		Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Brinell Hardness
0.40	0.52	1.00	2.39	....	1500° F. (815° C.) air quenched 1425° F. (775° C.) oil quenched 1100° F. (595° C) drawn.......	145 900	128 000	20	58.6	288
0.44	0.42	0.99	2.04	0.36	1475° F. (800° C) air quenched 1450° F. (790° C.) oil quenched 1100° F. (595° C.) drawn.. ...	184 250	173 250	18	56.8	340

0.35 per cent Carbon, 0.75 per cent Chromium, 1.50 per cent Nickel (Fig. 4):

The properties resulting from additions of nickel have long been known to be ductility, toughness, and shock resistance; and increased machineability in some cases. In a previous paragraph it was mentioned that nickel goes into solution with ferrite, thereby strengthening it to a great extent through grain refinement. Large grains in steel are not conducive to maximum impact values.

TABLE VI.—0.30 TO 0.40 PER CENT CARBON, 0.60 TO 0.75 PER CENT CHROMIUM, 0.30 TO 0.40 PER CENT MOLYBDENUM (FIG. 5).

Full-annealed, air cooled and drawn.

Chemical Analysis:

Carbon, per cent	0.30 to 0.40
Manganese, per cent	0.65 to 0.85
Chromium, per cent	0.75 to 1.00
Nickel, per cent	2.25 to 2.00
Molybdenum, per cent	0.30 to 0.40

Average Physical Properties:

Tensile strength, lb. per sq. in.	100 000
Yield point, lb. per sq. in.	80 000
Elongation in 2 in., per cent	22
Reduction of area, per cent	45

TABLE VII.—0.30 TO 0.40 PER CENT CARBON, 0.30 TO 0.40 PER CENT MOLYBDENUM, 0.60 TO 0.75 PER CENT CHROMIUM (FIG. 5).

Heat treatment: full-annealed, normalised, and drawn.

Chemical Analysis, per cent							Physical Properties					
Carbon	Manganese	Silicon	Phosphorus	Sulfur	Chromium	Molybdenum	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Type of Fracture	Izod Impact Value
0.42	0.91	0.38	0.046	0.036	0.70	0.33	119 500	89 000	18	40.9	Irregular	25
0.43	0.91	0.53	0.026	0.021	0.72	0.52	112 000	79 000	14	26.7	Flat	24
0.34	0.55	0.23	0.049	0.029	0.66	0.47	88 000	57 000	25	46.8	½ cup	30
0.36	0.80	0.40	0.045	0.032	0.68	0.38	105 000	72 000	17	42.0	....	..
0.33	0.87	0.42	0.042	0.037	0.70	0.40	99 000	67 000	19	40.0	. . .	..
						AVERAGE						
0.39	0.81	0.39	0.041	0.031	0.69	0.43	103 000	73 000	19	40.0	....	26

Nickel is generally used in connection with some other element, such as vanadium, chromium, or manganese. Simple nickel steels have properties similar to pearlitic manganese steels. Both have good elongation and reduction. The yield point is generally low and requires the addition of another element to increase it. Nickel is not lost through oxidation in the steel-making process. It is well to make the addition early in the heat to get proper dissemination.

Chromium in connection with nickel increases strength and hardness. Chromium oxidizes rather readily and therefore should be added rather late in making the heat. The loss in a well-operated acid electric furnace usually is from 5 to 10 per cent. Chromium is used with nickel in ratios of 1 to 2, and 1 to 2½. See Table IV and Fig. 4.

Table V gives data for two special nickel steels.

0.30 to 0.40 per cent Carbon, 0.60 to 0.75 per cent Chromium, 0.30 to 0.40 per cent Molybdenum (Fig. 5):

The addition of small amounts of molybdenum to chromium steel provides high strength and yield point. Such a mixture is especially applicable to large castings where depth hardening is necessary. It is regular practice to air quench this steel, and to draw it. See Tables VI and VII, and Fig. 5.

CHROMIUM STEELS FOR HIGH TEMPERATURES

The ability of a steel to withstand stress at room temperature is shown in a satisfactory manner by the regulation tests. Ordinarily steels do not fail under continued application of stress at ordinary temperatures when the stress does not exceed approximately one fourth of the tensil strength or one half of the yield point. This can be said to hold good up to a temperature of about 700° F. (20° C.).

The performances of the medium pearlitic and other cast steels under high-temperature and low-temperature conditions represent a problem involving a great deal of accurate investigational work necessitating special equipment, and requiring long periods of time. This is particularly true in connection with what is called creep testing, consisting of tests to determine the resistance of metal subjected to high temperatures continuously applied for extended periods, simultaneously with the application of stresses such as tension, and others involved when internal pressures are applied to metal parts.

The author considers it to be outside of the intended scope of this paper to attempt to give reliable data regarding performances under unusual temperature conditions. Thus far, no method for high-temperature testing has been standardized. Differences in equipment and procedure employed by various investigators have resulted, in some cases, in data of conflicting nature. The desirability of standardization and of accumulating dependable data resulted in the organization, in 1924, of the joint Research Committee on Effect of Temperature on the Properties of Metals.

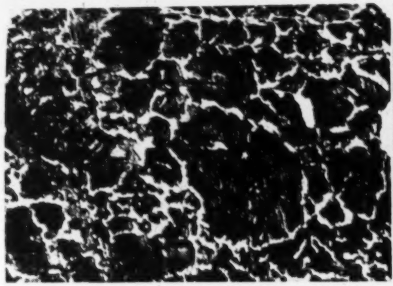

FIG. 1.—Photomicrographs of 0.40 to 0.50-per-cent Carbon Steel (× 100).

Annealed at 1600° F. (870° C.), reheated at 1500° F. (815° C.) and air cooled, drawn at 750° F. (400° C.), alcoholic nitric etch.

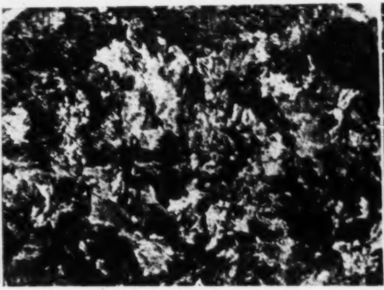

FIG. 2.—Photomicrographs of 0.80 to 0.90-per-cent Carbon Steel (× 100).

Annealed at 1600° F. (870° C.), reheated to 1500° F. (815° C.) and air cooled, drawn at 750° F. (400° C.) alcoholic nitric etch.

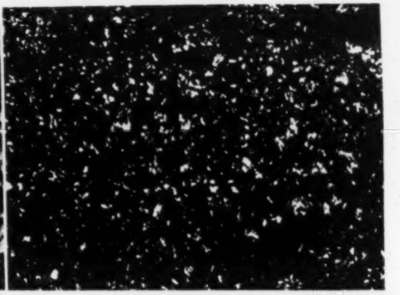

FIG. 3.—Photomicrographs of 0.30 to 0.40-per-cent Carbon, 0.30 to 0.40-per-cent Molybdenum Steel (× 100).

Annealed at 1800° F. (980° C.), normalized at 1600° F. (870° C.), drawn at 1250° F. (675° C.), alcoholic nitric etch.

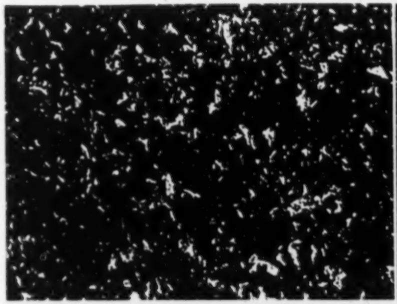

FIG. 4.—Photomicrographs of 0.30 to 0.40-per-cent Carbon, 0.75 to 1.00-per-cent Chromium, 1.00 to 1.50-per-cent Nickel Steel (× 100).

Annealed at 1700° F. (925° C.), air cooled at 1600° F. (870° C.), drawn at 1250° F. (675° C.), alcoholic nitric etch.

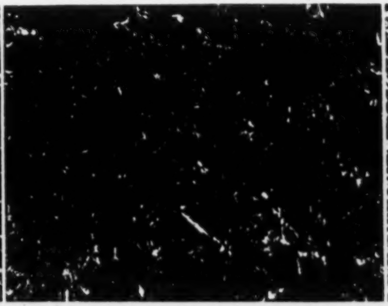

FIG. 5.—Photomicrographs of 0.30 to 0.40-per-cent Carbon, 0.60 to 0.75-per-cent Chromium, 0.30 to 0.40-per-cent Molybdenum Steel (× 100).

Annealed at 1800° F. (980° C.), normalized at 1600° F. (870° C.), drawn at 1250° F. (675° C.), alcoholic nitric etch.

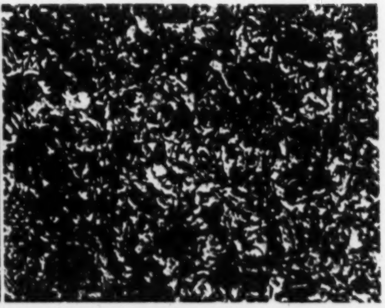

FIG. 6.—Photomicrographs of 0.30 to 0.40-per-cent Carbon, 1.05 to 1.20-per-cent Manganese Steel (× 100).

Air cooled from 1650° F. (900° C.), drawn at 1250° F. (675° C.), alcoholic nitric etch.

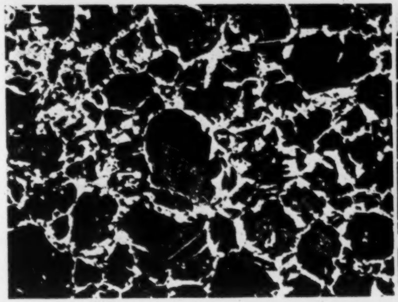

FIG. 7.—Photomicrographs of 0.30 to 0.40-per-cent Carbon, 1.40 to 1.55-per-cent Manganese Steel (× 100).

Full-annealed at 1650° F. (900° C.), reheated to 1550° F. (845° C.), and air cooled, then drawn at 700° F. (370° C.), alcoholic nitric etch.

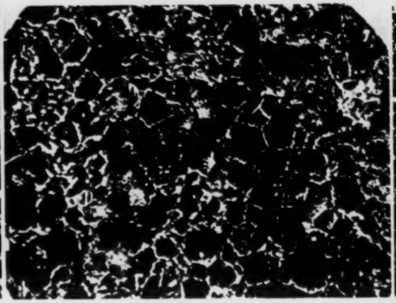

FIG. 8.—Photomicrographs of 0.30 to 0.40-per-cent Carbon, 1.70 to 2.00-per-cent Manganese Steel (× 100).

Annealed at 1650° F. (900° C.), normalized at 1550° F. (845° C.), drawn at 750° F. (370° C.), alcoholic nitric etch.

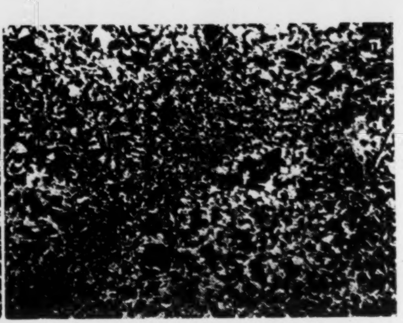

FIG. 9.—Photomicrographs of 0.30 to 0.40-per-cent Carbon, 1.40 to 1.55-per-cent Manganese, 0.10 to 0.15-per-cent Vanadium Steel (× 100).

Full-annealed at 1650° F. (900° C.), reheated to 1550° F. (845° C.), air cooled, and drawn at 700° F. (370° C.), alcoholic nitric etch.

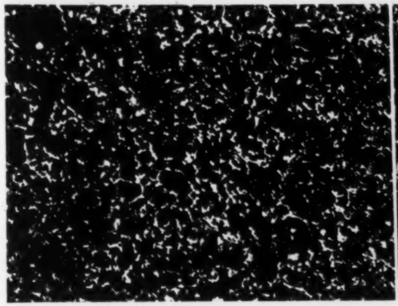

FIG. 10.—Photomicrographs of 0.30 to 0.40-per-cent Carbon, 1.30 to 1.55-per-cent Manganese, 0.60 to 0.75-per-cent Chromium Steel (× 100).

Full-annealed at 1650° F. (900° C.), reheated at 1550° F. (845° C.), air cooled, drawn at 700° F. (370° C.), alcoholic nitric etch.

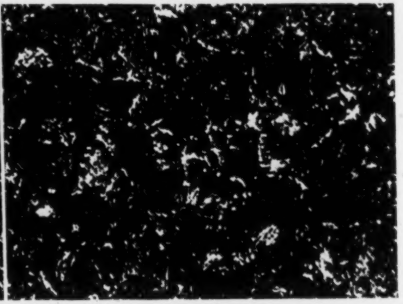

FIG. 11.—Photomicrographs of 0.30 to 0.40-per-cent Carbon, 1.40 to 1.55-per-cent Manganese, 0.45 to 0.55-per-cent Nickel Steel (× 100).

Full-annealed at 1650° F. (900° C.), normalized at 1550° F. (845° C.), drawn at 1250° F. (675° C.), alcoholic nitric etch.

The author refers those who are particularly interested in the behavior of cast steels in high- and low-temperature applications, to the volume published jointly by the American Society for Testing Materials and The American Society of Mechanical Engineers,[1] containing papers and discussions presented at a symposium held under the auspices of the two societies in June, 1931. In that book is found a comprehensive amount of data relating to the performances of cast steels in the medium pearlitic class under high- and low-temperature conditions, included in a paper covering cast-carbon and low-alloy steels, written for the symposium, by R. A. Bull.

TABLE VIII.—0.30 TO 0.40 PER CENT CARBON, 1.05 TO 1.20 PER CENT MANGANESE (FIG. 6).

Heat treatment: air cooled from 1650° F. (900° C.), and drawn at 1250° F. (675° C.).

Chemical Analysis, per cent					Physical Properties			
Carbon	Manganese	Silicon	Phosphorus	Sulfur	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
0.34	1.12	0.47	0.024	0.032	80 500	41 000	30	47.4
0.32	1.16	0.36	0.038	0.040	73 500	41 500	31	52.3
0.28	1.16	0.32	0.040	0.042	80 700	41 000	27	42.0
0.32	1.16	0.30	0.048	0.044	88 000	46 000	27	39.4
0.32	1.08	0.27	0.036	0.037	80 500	41 000	24	44.2
AVERAGE								
0.32	1.14	0.36	0.037	0.038	81 000	42 000	28	45.0

TABLE IX.—0.30 TO 0.40 PER CENT CARBON, 1.25 TO 1.40 PER CENT MANGANESE.

Air cooled from 1650° F. (900° C.), and drawn at 1250° F. (675° C.).

Chemical Analysis, per cent					Physical Properties			
Carbon	Manganese	Silicon	Phosphorus	Sulfur	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
0.30	1.32	0.47	0.028	0.034	84 500	48 000	25.5	54.0
0.34	1.34	0.33	0.032	0.026	86 000	45 000	24.0	49.8
0.33	1.34	0.41	0.024	0.035	97 000	73 000	22.0	51.0
0.33	1.36	0.33	0.024	0.031	93 750	67 000	27.0	61.1
0.29	1.28	0.35	0.019	0.026	82 500	53 000	29.0	63.0
AVERAGE								
0.32	1.33	0.38	0.026	0.031	88 000	57 000	25.0	56.0

PEARLITIC MANGANESE STEELS

While manganese is added as deoxidizer, it also plays the part of an alloy. Ordinarily the manganese content of a common grade steel is about 0.50 to 0.85 per cent. Among the medium manganese steels there appear to be four groups, as follows:

0.30 to 0.40 per cent carbon, 1.05 to 1.35 per cent manganese
0.30 to 0.40 per cent carbon, 1.35 to 1.55 per cent manganese
0.30 to 0.40 per cent carbon, 1.70 to 2.00 per cent manganese
0.30 to 0.40 per cent carbon, 2.00 to 3.00 per cent manganese

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[1] Symposium on Effect of Temperature on the Properties of Metals, published jointly by the American Society for Testing Materials and The American Society of Mechanical Engineers (1931).

TABLE X.—0.30 TO 0.40 PER CENT CARBON, 1.40 TO 1.55 PER CENT MANGANESE (FIG. 7).

Heat treatment: full-annealed at 1650° F. (900° C.), air cooled from 1550° F. (845° C.), and drawn at 700° F. (370° C.).

Chemical Analysis, per cent					Physical Properties				
Carbon	Manganese	Silicon	Phosphorus	Sulfur	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value
0.37	1.56	0.51	0.030	0.032	101 500	55 000	27.0	44.5	..
0.40	1.54	0.44	0.039	0.030	100 500	54 700	25.5	50.5	19
0.36	1.40	0.49	0.033	0.026	95 000	52 000	27.0	53.0	..
0.36	1.34	0.42	0.037	0.025	86 000	46 500	32.0	57.8	21
0.32	1.40	0.39	0.035	0.026	93 000	52 500	26.0	55.7	20
AVERAGE									
0.36	1.45	0.45	0.035	0.028	95 200	52 000	27.1	52.3	20

TABLE XI.—0.30 TO 0.40 PER CENT CARBON, 1.70 TO 2.00 PER CENT MANGANESE (FIG. 8).

Heat treatment: full-annealed at 1650° F. (900° C.), air cooled from 1550° F. (845° C.), drawn at 750° F. (400° C.).

Chemical Analysis, per cent					Physical Properties				
Carbon	Manganese	Silicon	Phosphorus	Sulfur	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value
0.35	1.75	0.35	.....	.....	107 200	66 000	26.0	57.5	25
0.35	1.75	0.50	.....	.....	111 600	68 800	25.5	51.6	17
0.34	1.68	0.31	0.033	0.029	103 000	55 000	25.0	51.0	21
0.34	1.85	0.28	0.027	0.027	110 000	63 000	22.0	44.0	..
0.32	1.76	0.28	.....	.....	103 000	53 000	25.0	56.0	29
AVERAGE									
0.34	1.77	0.34	.....	.....	107 000	61 000	24.0	52.0	23

TABLE XII.—EFFECT OF CARBON AND MANGANESE ON PHYSICAL PROPERTIES.

Chemical Analysis, per cent			Physical Properties				
Carbon	Manganese	Silicon	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value
0.29	1.20	0.28	77 500	50 500	32.0	55.4	..
0.32	1.16	0.30	88 000	46 000	27.0	40.0	34
0.34	1.12	0.47	80 500	41 000	30.0	47.4	..
0.35	1.40	0.40	102 650	60 850	27.5	58.0	26
0.30	1.56	0.28	92 000	50 000	30.0	60.0	27
0.33	1.50	0.30	94 000	51 000	27.0	59.0	..
0.34	1.53	0.29	95 000	54 000	28.0	59.0	22
0.37	1.53	0.28	99 000	57 000	22.0	44.0	..
0.41	1.50	0.30	112 000	62 000	18.0	40.0	18
0.34	1.68	0.31	103 000	55 000	25.0	51.0	21
0.35	1.67	0.29	106 000	57 000	24.0	50.0	..
0.37	1.66	0.28	109 000	58 000	22.0	48.0	19
0.39	1.66	0.28	109 000	60 000	15.0	32.0	..
0.32	1.76	0.28	103 000	53 000	25.0	56.0	29
0.33	1.74	0.30	105 000	53 000	24.0	56.0	..
0.34	1.76	0.27	107 000	55 000	24.0	54.0	24
0.35	1.75	0.30	107 000	56 000	24.0	51.0	25
0.36	1.74	0.28	108 500	51 000	22.0	46.0	..
0.37	1.74	0.32	109 000	60 500	20.0	34.0	20
0.39	1.75	0.29	115 000	62 000	19.0	39.0	..
0.40	1.76	0.30	115 600	64 000	18.0	31.0	18
0.34	1.85	0.28	110 000	63 000	22.0	44.0	26
0.37	1.80	0.30	117 000	66 500	20.0	42.0	..
0.38	1.79	0.29	116 000	65 000	18.0	38.0	..
0.37	1.90	0.29	117 000	65 000	21.0	46.0	12

To these groups there can be added nickel, chromium, vanadium, and molybdenum, as in the case of the grade containing 0.50 to 0.85 per cent manganese, with advantage in certain applications. See Tables VIII, IX, X, and XI, and Figs. 6, 7, and 8.

To ascertain the effect of increasing the manganese, data on 25 heats were tabulated, as shown in Table XII. The heat treatment was as follows: Heated at 1650° F. (900° C.), air cooled from 1550° F. (845° C.), and drawn at 700° F. (370° C.). The heats can be divided into five groups, as follows:

	Carbon, per cent	Manganese, per cent	Silicon, per cent	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
Group 1	0.32	1.16	0.35	82 000	46 000	30.0	47.5
Group 2	0.35	1.51	0.31	97 500	55 800	25.0	53.0
Group 3	0.36	1.67	0.29	107 000	57 500	21.5	45.0
Group 4	0.36	1.75	0.29	109 000	57 000	22.0	46.0
Group 5	0.36	1.83	0.29	115 000	65 000	20.0	43.0

As the manganese and carbon increase, the yield points and tensile strengths increase, at the expense of the elongation and reduction. See Table XIII. It should be kept in mind, in examining Table XII, that one heat treatment procedure was applied throughout. The merits of some of the groups might have been distinctly changed by another heat treatment.

Group 4 shows that where the manganese remains constant, the tensile strength and yield point increase with each added point of carbon. The impact value is reduced as the carbon increases. After drawing, the medium magnanese steels should be air cooled, and in some cases quenched, in order to get the best results. Impact and yield points are increased after oil quenching and drawing. The pearlitic manganese steels have low impact and yield point values in the full-annealed condition. These properties are improved by the addition of another element, such as vanadium, molybdenum, zirconium, etc. The author wishes to emphasize that full-annealing is not the best treatment for the higher manganese steels, to develop their true value.

A steel having contents of 0.34 per cent carbon and 2.50 per cent manganese, when full-annealed, oil quenched, and drawn, showed the following results:

Tensile strength, lb. per sq. in.	96 000
Yield point, lb. per sq. in.	70 000
Elongation in 2 in., per cent	30
Reduction of area, per cent	56
Izod impact value, ft-lb.	75

TABLE XIII.—EFFECT OF MANGANESE INCREASE WITH CARBON CONSTANT.

Chemical Analysis, per cent		Physical Properties				
Carbon	Manganese	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value
0.34	0.80	83 000	39 500	27	40.0	28
0.34	0.92	84 500	41 000	26	38.8	23
0.34	1.12	80 500	41 000	30	47.4	16
0.34	1.34	86 000	45 000	24	49.8	18
0.34	1.53	95 000	54 000	28	59.0	22
0.34	1.68	103 000	55 000	25	51.0	21
0.34	1.76	107 000	55 000	24	54.0	24
0.34	1.85	110 000	63 000	22	44.0	26

TABLE XIV.—0.30 TO 0.40 PER CENT CARBON, 1.40 TO 1.55 PER CENT MANGANESE, 0.10 TO 0.15 PER CENT VANADIUM (FIG. 9).

Chemical Analysis, per cent				Physical Properties				
Carbon	Manganese	Silicon	Vanadium	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value
0.35	1.40	0.40	0.10	103 200	70 500	25.0	51.9	43.0
0.35	1.40	0.40	0.10	100 700	74 500	30.5	61.8	57.5
0.29	1.33	0.42	0.11	90 000	64 350	31.0	63.5	73.5
0.29	1.38	0.43	0.10	93 300	69 550	30.8	61.1	61.0
0.32	1.38	0.41	0.10	106 550	75 150	25.0	49.9	....
AVERAGE								
0.32	1.38	0.41	0.10	98 000	70 200	28.0	57.6	58.7

TABLE XV.—0.30 TO 0.40 PER CENT CARBON, 1.30 TO 1.45 PER CENT MANGANESE, 0.60 TO 0.75 PER CENT CHROMIUM.

Heat treatment: full-annealed at 1650° F. (900° C.), air cooled from 1550° F. (845° C.) and drawn at 700° F. (370° C.).

Chemical Analysis, per cent				Physical Properties				
Carbon	Manganese	Silicon	Chromium	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value
0.35	1.40	0.50	0.60	110 000	71 000	25	56	23
0.40	1.40	0.50	0.60	120 000	75 000	23	52	10
0.45	1.40	0.50	0.60	130 175	83 200	17	33	14
0.38	1.37	0.46	0.65	130 800	74 600	20	51	..
0.37	1.34	0.43	0.68	127 000	69 200	20	52	..

TABLE XVI.—0.30 TO 0.40 PER CENT CARBON, 1.40 TO 1.55 PER CENT MANGANESE, 0.45 TO 0.55 PER CENT NICKEL (FIG. 11).

Chemical Analysis, per cent						Physical Properties				
Carbon	Manganese	Silicon	Phosphorus	Sulfur	Nickel	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value
0.36	1.46	0.44	0.028	0.026	0.49	96 000	56 000	27.0	57.0	36
0.32	1.50	0.36	.....	.....	0.45	91 500	52 500	30.0	59.1	..
0.34	1.34	0.46	.....	.....	0.38	94 500	57 750	26.0	51.7	..
0.39	1.29	0.49	0.037	0.042	0.64	101 000	58 000	24.5	49.4	..
AVERAGE										
0.34	1.48	0.44	.....	.....	0.47	94 000	54 500	28.5	58.0	..

A steel containing 0.27 per cent carbon, 2.67 per cent manganese, 0.24 per cent nickel, 0.44 per cent molybdenum, and 0.20 per cent silicon, after being full-annealed, quenched from 1450° F. (790° C.), then drawn at 1250° F. (675° C.), followed by oil quenching, gave results as follows:

Tensile strength, lb. per sq. in.	108 000
Yield point, lb. per sq. in.	86 000
Elongation in 2 in., per cent	26
Reduction of area, per cent	61
Izod impact value, ft-lb.	106 to 111

A steel having 0.33 per cent carbon, 2.54 per cent manganese, 0.34 per cent nickel, and 0.51 per cent silicon, after being full-annealed, oil quenched from 1550° F. (845° C.), then drawn at 1300° F. (705° C.), resulted as follows:

Tensile Strength, lb. per sq. in.	100 000
Yield point, lb. per sq. in.	73 000
Elongation in 2 in., per cent	29
Reduction of area, per cent	56
Izod impact value, ft-lb.	70 to 75

0.30 to 0.40 per cent Carbon, 1.40 to 1.55 per cent Manganese, 0.10 to 0.15 per cent Vanadium:

When a small amount of vanadium is added to pearlitic manganese steel a very distinct effect is noticed, in that the yield point is raised and the impact value nearly doubled. The grain refinement also exhibits a remarkable contrast, compared with plain medium manganese steel. See Table XI. The physical properties are in general improved. See Table XIV and Fig. 9.

0.30 to 0.40 per cent Carbon, 1.30 to 1.40 per cent Manganese, 0.60 to 0.75 per cent Chromium:

Steel of this analysis is useful for abrasive resistance and for many applications requiring high physical properties. The impact values are medium; however, a small vanadium addition corrects this condition. See Table XV and Fig. 10.

0.30 to 0.40 per cent Carbon, 1.40 to 1.55 per cent Manganese, 0.45 to 0.55 per cent Nickel (Table XVI and Fig. 11):

The author has found that the effect of nickel on steels containing medium manganese tends to eliminate temper brittleness, after drawing. Normalizing gives satisfactory properties for many purposes. The percentage of nickel can be varied according to the manganese content, for example:

1.05 to 1.20 per cent manganese, 1.00 per cent nickel
1.35 to 1.55 per cent manganese, 0.75 per cent nickel
1.70 to 2.00 per cent manganese, 0.60 per cent nickel
2.00 to 3.00 per cent manganese, 0.45 per cent nickel

0.20 to 0.30 per cent Carbon, 1.50 to 1.60 per cent Nickel, 0.10 to 0.20 per cent Vanadium:

As the percentage of nickel increases, elongation and impact values are increased. The presence of vanadium is also of value, with relation to grain refinement, and consequently, shock-resisting qualities. Nickel contents of over 2 per cent are used, while the manganese can be varied, as referred to in a previous table. See Table XVII.

TABLE XVII.—0.20 TO 0.30 PER CENT CARBON, 1.50 TO 1.60 PER CENT NICKEL, 0.10 TO 0.20 PER CENT VANADIUM.

Heat treatment: full-annealed, and drawn.

Chemical Analysis, per cent							Physical Properties				
Carbon	Manganese	Silicon	Phosphorus	Sulfur	Nickel	Vanadium	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Value
0.25	0.94	0.39	0.033	0.029	1.56	0.11	92 000	61 000	27.0	54.0	60.0
0.20	0.87	0.33	.....	.....	1.50	0.12	85 375	59 000	29.5	59.1	....
0.22	0.74	0.34	.....	.....	1.55	0.10	88 730	56 070	29.5	58.2	63.0
0.26	0.97	0.30	.....	.....	1.54	0.11	90 000	60 500	25.5	50.9	47.0
0.32	1.07	0.28	.....	.....	1.58	0.11	96 500	70 500	28.0	59.9	59.5
					AVERAGE						
0.246	0.912	0.33	.....	.....	1.55	0.11	91 000	61 000	28.0	57.0	....

CONCLUSIONS

The author believes that consistent values can be obtained in the regular foundry production of the pearlitic steels. It should be remembered that the data reported herein are not experimental, but are representative results obtained by different foundries, covering extensive periods of time, in routine manufacture.

It is to be noted from the data quoted that new types of steels have been developed, as follows:

0.30 to 0.40 per cent carbon, 0.50 to 0.85 per cent manganese, with alloys
0.30 to 0.40 per cent carbon, 1.05 to 1.35 per cent manganese, with alloys
0.30 to 0.40 per cent carbon, 1.40 to 1.55 per cent manganese, with alloys
0.30 to 0.40 per cent carbon, 1.75 to 2.00 per cent manganese, with alloys
0.30 to 0.40 per cent carbon, 2.00 to 3.00 per cent manganese, with alloys

To obtain the best results from steels having a manganese content above 1.50 per cent, special treatments should be given, to avoid temper brittleness. Steels can have many good physical properties while deficient in shock resistance, which seems to be a function of grain refinement. Special heat treatment or the addition of another element may provide good impact values. It seems to the author that much benefit would be derived by standardization, which can be facilitated by specifications. The specification is rightly considered as the starting basis for selecting and evaluating the correct steel for the application. It is hoped that the data given in this paper will increase the field of cast steels by demonstrating impressive physical properties obtainable from a great many varieties of medium pearlitic steels admirably adaptable for castings.

DISCUSSION

Mr. P. E. McKinney.[1]—This paper is an excellent tabulation of the inherent properties of the various alloy additions commonly used in the alloy steel casting industry. I think that if it is used as such it is going to serve a very valuable purpose for making direct comparisons, presumably under more or less standardized conditions, in which case it will serve as what we might call property charts.

There is one possible danger of a tabulation of this kind being too literally interpreted by users and producers. While it is true that the physical values have been taken from the product of regular casting heats, I think it is necessary to regard some of them somewhat as the steel trade does the standard physical property charts on, for instance, 1-in. bars. In the alloy-steel industry we have learned a lot about the effect of mass action. We know that the properties that we get on 1-in. rounds or up to 6-in. rounds cannot even be approached when we get into very much heavier masses, and we have to set up requirements which are applicable, based on experience from testing material from these heavier sections. It would be unfortunate if we were to take these ideal values on smaller castings and apply them in the expectation of duplicating some of them in the larger and heavier castings, because we will not approach such values in actual practice. Failure to realize this will result in disappointment in the possibilities of alloy steels, as was suggested in some of the discussions of Mr. Bull's paper[2] where reference was made to the differences that existed between coupons and the body of the casting. Mass action has a great part to play. I think, when properly used, as brought out by Mr. Bull in his comments on inspection, these tabulations will be an excellent contribution, but if they are accepted by the trade as representative of what the designer can figure on getting out of a casting member, irrespective of its size, location, and other conditions, it will not be very good for the industry as a whole.

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[1] Metallurgical Engineer, Bethlehem Steel Co., Inc., Bethlehem, Pa.

[2] See p. 106.

CASTINGS OF CORROSION-RESISTANT STEELS

By Jerome Strauss[1]

Introduction

The corrosion-resistant steels are essentially alloys of iron and chromium, the properties of which are improved in different ways for different applications through the addition of other elements. While important effects are secured by the introduction of carbon, silicon, sulfur (as specific sulfides), molybdenum, tungsten, titanium and vanadium, the element incorporated most frequently and in the largest percentage is nickel. Because of this fact and one other—the continuous series of commercial alloys for similar purposes extending from the realm of preponderant iron proportion to that dominantly nickel—it is often convenient to consider them all as belonging to the iron-chromium-nickel ternary system, in some instances modified by important though small amounts of other metals and non-metals.

Within this ever-widening group of alloys are included the greater number of those employed for exposure to the severe conditions to which metals are subjected in many modern industrial processes—the attack of polluted atmospheres, natural waters, sea water, highly reactive chemicals, crude petroleum and the various refinery products at both atmospheric and elevated temperatures, air and various furnace gases over a wide temperature range, and molten salts and metals. Such diverse and increasing uses make it difficult to keep abreast of progress. Hence it is the aim of this paper to present to designing engineers and to others not in constant and intimate contact with the field, a brief résumé of its status with the hope that it may lead to a clearer understanding of the merits and shortcomings of each type, and of the manufacturer's problems. By such means perhaps, user and producer may be led to cooperate, avoid costly failures, and bring forth new accomplishments.

General Considerations Affecting Alloy Selection

In another paper[2] of this symposium, the influence of design upon the soundness and other qualities of steel castings, with the coincident effect upon rejections, failures and ultimate costs, is considered in a most complete manner. It is intended at this point merely to focus attention upon the details of that paper since the numerous features brought forth therein must be considered many times more carefully in the design and manufacture of these highly alloyed steels than in the production of the carbon and low-alloy steels. Aside from numerous troubles that may arise in the melting, alloying, and conditioning of the molten metal prior to casting, which only indirectly concern the designer, shrinkage, porosity and such surface irregularities as "cold-shuts" are very real and sometimes staggering defects that he can greatly aid in minimizing. Founders experienced in the production of these alloys have recorded real progress during the past five years, so that cooperative design possesses in most instances excellent chances of success.

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[1] Chief Research Engineer, Vanadium Corporation of America, Bridgeville, Pa.

[2] F. A. Lorenz, Jr., "Notes on the Design of Steel Castings," see p. 58.

From the specific information on properties to be given, it will be observed that each application requires individual consideration. Temperature, surrounding medium, machining requirements, service stresses and general design features, each influences the selection of the most economical and otherwise satisfactory alloy. This has resulted in innumerable composition modifications, all of which, obviously, cannot be recorded here. But by including the principal alloys and indicating the effects of small changes in composition, it is hoped to adequately present the case.

There is a notable lack of precision and general agreement in much of the available data, and this has necessitated the design of castings and the selection of alloys based, in large measure, on experience and rough empirical knowledge. Principal among the sources of information of questionable value are laboratory corrosion tests. Of like importance are many of the determinations of mechanical properties (principally in tension, though also impact, endurance, wear, etc.) at elevated temperatures. The latter problem is doubly complicated in the case of the cast alloys by lack of agreement upon a suitable method for the preparation of test bars. A remedy in this case may however be expected shortly as a result of study of the problem by the American Society for Testing Materials.

Corrosion tests have been frequent causes for misapplication and failure. Lack of recognition of essential features of a given service or minimization of their importance leads to the design of poor or ineffective testing procedures. Likewise too great intensification of one variable, such as temperature, concentration of a corroding agent, speed of agitation, pressure in wear testing, etc., resulting from a desire for a too greatly accelerated test, frequently produce data of no real value. Methods of expressing results must obviously fit the needs of each case. In one instance weight loss (or gain) may be the best indication of serviceability, while in others penetration rate or alteration in some important mechanical property is the better indication. Obviously, actual use under the intended conditions, is the most reliable means of selection, but preliminary assistance may be secured by testing methods deviating only slightly from the conditions of use. Suitably stressed specimens exposed to service conditions often afford a very conclusive indication of degree of value.

Available data on strength properties or load-carrying ability at elevated temperatures is not always directly useful—quantitatively. This is especially true of the cast alloys: first, because of the relatively smaller amount of this testing that has been carried out on cast materials; second, because of the present lack of knowledge of methods for the production of suitably sound, uniform and representative specimens for testing; and third, due to the lack of general agreement concerning the testing apparatus, procedure and methods of expressing and interpreting results. All of these shortcomings are in process of removal, but in the meantime recourse must be had to the limited published data and to records of performance. Short-time tension tests determining, in a few hours, characteristics similar to those disclosed in "static" room-temperature tests may be of value to the metallurgist seeking improvement in materials or manufacturing processes, but are of limited value to the designing engineer. Methods endeavoring to predict in a hundred hours, or less, the deformations that will result from many thousands of hours of use, have not yet been proved applicable to all materials or all load and temperature conditions, since, in the present state of our knowledge, time-extension curves are not susceptible of mathematical expression. Quantitative design information is thus to be secured only from constant-load tests of long duration if these expensive metals are to be utilized in the most economical manner, yet without jeopardy to equipment and operations. And as allowable dimensional change decreases, the need for close scrutiny of testing methods and results rapidly increases.

Thus, while the future will witness the development of the same degree of precision in the design and use of the special alloys employed in chemically active media and at high temperatures, as is true today of the older and more simple steels at atmospheric temperature, present utilization must in large measure be based upon experience with similar parts under similar or identical conditions of use. In the absence of such experience it is possible only to select one or more alloys which, upon the basis of general information available, appear likely to meet the requirements, and then actually to try them out upon as large a scale as is permissible. The following descriptions are intended to serve as guides of such nature, giving numerical data only where the origin appears to be fully reliable.

In the previous paragraphs, consideration has been given solely to those properties which are not only least well known but which therefore are at present subject to the greatest study and, due to presenting considerable experimental difficulty, are involved in much controversy. Other properties, however, are of importance. A knowledge of thermal expansion coefficients is necessary in avoiding failure by buckling and cracking when these metallic alloys form part of a structure composed of other materials, or when local overheating occurs in a single part. The effects produced by fluctuations in supposedly constant temperature operations, and by the speed and frequency of heating and cooling cycles likewise demand information on rates of expansion. Specific heat and thermal conductivity are of importance through influencing, in connection with other factors, rates of heat transfer, thus affecting process speeds and actual temperature differences between the surfaces of the walls of heated vessels. Other properties may be required to be known in specific applications, and none of them should be overlooked.

PROPERTIES OF THE ALLOYS

Iron-Chromium Alloys:

It is convenient, in dealing with these alloys, to consider the plain chromium steels first. Of these the very low chromium steel of the so-called "stainless iron" type has been used in the cast form to only a very limited degree. Data concerning this steel (alloy No. 1) appear in Table I. For this alloy, as for the others in Table I, a number of features necessitate prior explanation. The composition given is in every instance a nominal one. Each manufacturer of any alloy works within some range of composition which is not always the same for all producers, but an indication of the effect of change of composition upon some of the properties will permit evaluation of these differences. The assumption is made that certain of the physical properties are not appreciably different in cast and wrought metal of like composition, as for example thermal conductivity, specific heat, etc., so that data on the cast metals being scarce, information obtained on the wrought products is included. For like reason, and due also to the fact that castings with their coarser microstructure, are generally regarded as superior in sustaining loads at elevated temperatures than are wrought products of the same composition, strength properties of wrought material at elevated temperatures are quoted where other data are not obtainable. The use of these values may, of course, result in designs that are unduly strong, but at least the error will be on the safe side.

This steel, alloy No. 1, is mildly air-hardening and is usually supplied air-quenched from 950 to 1000° C. and tempered at 600° C. or higher. It may be case-hardened in the same manner as carbon or low-alloy steels, although at a slightly higher temperature, thus acquiring a hard surface yet retaining a tough core. In this state, however, it is less serviceable in corroding media. For a given carbon content the corrosion resistance increases with the chromium content, although this effect is very much less on a case-hardened surface. Finely divided sulfides are sometimes introduced to improve machineability, while nickel up to 2 per cent has been used to reduce grain size, improve shock resistance, and slightly increase resistance to corrosion. Silicon has been used up to 2 per cent and confers improved casting qualities as well as added corrosion resistance.

Castings, hardenable by quenching and tempering to a Brinell hardness of 500 or slightly higher, have been produced, in limited quantity, of a composition very similar to that of the foregoing steel, but with 0.35 per cent carbon. The thermal and electrical properties are approximately the same and the behavior in fabricating operations similar while the mechanical properties are of course dependent upon heat treatment. With a Brinell hardness of 500 these approximate:

Tensile strength, lb. per sq. in.	250 000
Yield point, lb. per sq. in.	180 000
Elongation in 2 in., per cent	3.0
Reduction of area, per cent	10.0

This alloy is employed for bearing or abrasion-resisting surfaces in the same media as the low-carbon steel of like chromium content, but the resistance to corrosion is slightly lower than that of the low-carbon type, even when the former is fully hardened (the most resistant state).

Still further increase in carbon (to about 1.50 to 2.25 per cent) in the 13.0-per-cent chromium steels and the addition of one or more of the elements, cobalt, tungsten, molybdenum and vanadium, in amounts of 0.5 to 4.0 per cent, yield steel castings (used in moderate tonnage) for dies and other abrasion-resistant parts. They are not, however, possessed of any unusual surface stability, either at low or high temperatures.

Although the tonnage of the low-chromium steels, in cast form, is low, considerable use has been found for castings of low-carbon steels of a higher chromium content (alloy No. 2), possessing the properties shown in Table I.

This steel is an extremely useful one and has found its greatest single application in nitric acid manufacturing and handling equipment. It is generally marketed air-cooled from 1000 to 1050° C. and reheated to about 800° C. It may be used at elevated temperatures to a limited degree, the limitation being imposed by two ranges of embrittlement. Long exposure between about 350 and 550° C. results in a structural change, made evident by extreme brittleness upon cooling to room temperature. This embrittlement does not exist at the temperature at which it develops and is removable by reheating to about 780 to 820° C. but will appear again upon re-exposure to the former temperature; its occurrence is not greatly influenced by changes in composition within the ranges ordinarily employed. The second zone is one of the development of permanent grain growth (capable of correction only by working) and consequent embrittlement beginning at about 840° C.; this lower limit is raised as silicon or chromium is decreased, or carbon is increased.[1] This latter difficulty has been minimized by raising the carbon to 0.20 per cent, holding the chromium just below the usual lower limit of this type, namely 16 per cent, and adding 1 to 2 per cent nickel in an effort to offset the loss in corrosion resistance. Another method is to increase the carbon to 0.30 per cent, guarding against possible greater loss in corrosion resistance by raising the chromium to 20 per cent (which is not objectionable in the presence of the much higher carbon content) and by adding 1 per cent of copper.

In the carbon percentage tabulated, the steel is not greatly hardenable by heat treatment, but by an increase in carbon it is developed into a suitable die steel, possessed of the same heat resistance as the low-carbon product, but not as resistant to liquid corrosive media at moderate temperatures. A number of commercial steels fall within this classification, the carbon content being higher when the chromium is higher, within the following range:

Carbon, per cent	0.6 to 1.2
Chromium, per cent	15.5 to 23.0
Silicon, per cent	0.5 to 2.0

Cobalt, molybdenum, vanadium and tungsten are frequently added in small percentages and effect marked improvement in performance. Further increase of carbon, in the presence of tungsten, characterizes a cast product not dependent upon heat treatment for its great hardness (600 to 680 Brinell). Unmachineable and rather brittle, it sacrifices these properties for a degree of abrasion resistance that has been productive of success in ceramic molds and metal-working dies. Its composition is:

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[1] It should be noted that the alloy is not usable much above this temperature, due to free oxidation. This second zone of embrittlement is important, however, in welding and in cooling after casting.

Carbon, per cent	2.35
Chromium, per cent	18.0
Tungsten, per cent	12.0
Silicon, per cent	2.5

Further increase in chromium content has resulted in a casting steel of much merit, the properties of which are shown in Table I (alloy No. 3).

This most highly alloyed of the plain chromium steels loses toughness after long exposure to certain high temperatures, but the ranges of temperature are somewhat higher than in the lower chromium type, and, the initial toughness being less, the loss is not so apparent. The brittleness develops either between 400 and 600° C. or above 900° C., in the latter case resulting from slow grain growth. As in the lower chromium steel, the poor mechanical properties do not prevail at the high temperature but appear only after cooling. Castings of the 28-per-cent chromium steel show great variation in grain size as a result of small changes in pouring and mold temperatures This condition appears to be emphasized by a high silicon content (2 per cent), sometimes added to insure fluidity and soundness of castings and is often controlled by raising the carbon or by the addition of from 3 to 8 per cent of nickel. Machining qualities are excellent if the total amount of carbon plus silicon is considerably below 1.5 per cent; above this value, ease of machining decreases rapidly. A characteristic of all the chromium steels is most noticeable in this composition—a film of oxide formed during pouring, spreads irregularly over the casting surface. It gives the appearance of a large number of cold-shuts, but is generally only skin deep and is not a defect or an indication of poor quality. None of the chromium steels, including this most stable 28-per-cent alloy, is suitable in contact with alkali metal salts at high temperature under oxidizing conditions; in reducing atmospheres they are more satisfactory, but they are not to be generally recommended for use with these compounds. Castings of this composition are usually annealed, the temperature depending somewhat upon the carbon content, but in any case, cooling below 600° C. should be rapid.

Higher carbon content (2.0 to 3.0 per cent) converts this alloy into a most interesting abrasion-resistant product, successful in rolls for the fabrication of sheet metal and in sand pumps in mines. As

TABLE I.—PROPERTIES OF

Alloy	Chemical Composition, per cent					Physical Properties								Machining Behavior	Welding Behavior
						At Room Temperature					At Elevated Temperature				
	Carbon	Chromium	Nickel	Manganese	Silicon	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Strength, ft-lb.	Temperature, deg. Cent.	Stress Producing 1 per cent Elongation in 10,000 hours	Stress Producing 1 per cent Elongation in 100,000 hours		
IRON-CHROMIUM ALLOYS															
No. 1	0.10	13.0	....	...	1.0	75 000 to 95 000	45 000 to 60 000	18 to 24	30 to 50	....	540[a] 595[a] 650[a]	13 000[a] 5 200[a] 2 100[a]	4 500 to 10 000[a] 2 000 to 4 000[a] 1 000 to 1 600[a]	About same as medium carbon steel.	Satisfactory, if welds annealed and air cooled.
No. 2	0.12	18.0	....	...	1.0	75 000 to 110 000	45 000 to 70 000	10 to 20	15 to 35	3 to 10	425[a] 540[a] 595[a] 650[a]	8 500[a] 5 200[a] 2 100[a]	10 000[a] 4 200 to 7 000[a] 1 950 to 4 500[a] 900 to 1 600[a]	About same as medium carbon steel.	Welding not recommended for other than very thin sections.
No. 3	0.50	28.0	....	...	1.0	40 000 to 60 000	30 000 to 45 000	0 to 2	0 to 5	1 to 5	540[a] 595[a] 650[a] 760[a]	....	4 650 1 950 750 150	About same as medium carbon steel.	Satisfactory; slow cooling required to 600° C. then rapid cooling.
IRON-CHROMIUM-NICKEL ALLOYS															
No. 4	0.20	8.0	20.0	...	1.0	75 000 to 85 000	40 000 to 50 000	20 to 30	20 to 30	....	540[a] 595[a] 650[a] 705[a] 815[a]	20 500 to 25 000[a] 11 000 to 11 800[a] 5 600 to 6 000[a] 4 000[a] 1 100[a]	20 000[a] 9 500[a] 5 500[a] 3 600[a] 750[a]	Tough; intermediate between carbon steel and monel metal.	Satisfactory.
No. 5	0.15	18.0	8.0	...	1.0	70 000 to 80 000	25 000 to 40 000	40 to 75	40 to 75	50 to 105	480[a] 540[a] 595[a] 650[a] 705[a] 815[a]	.... 17 000[a] 9 500 to 10 500[a] 7 000 to 9 500[a] 7 000[a] 800[a]	15 000 to 20 000[a] 10 000 to 15 000[a] 7 000 to 8 500[a] 4 000 to 5 500[a] 2 600 to 3 500[a] 650 to 750[a]	Tough; intermediate between carbon steel and monel metal.	Satisfactory, if heat treated after welding.
No. 6	0.06	18.0	8.0	...	1.0	70 000 to 80 000	25 000 to 30 000	40 to 75	40 to 75	60 to 105	480[a] 540[a] 595[a] 650[a] 705[a]	....	18 000 to 20 000[a] 12 000 to 15 000[a] 7 500 to 8 500[a] 4 500 to 5 500[a] 2 500 to 3 500[a]	Tough; intermediate between carbon steel and monel metal.	Satisfactory; desirable to heat treat after welding.

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[a] Data on the wrought alloy.

CORROSION-RESISTANT STEELS.

Coefficient of Thermal Expansion		Melting Temperature, deg. Cent.	Specific Gravity	Thermal Conductivity		Specific Heat	Specific Electric Resistance		Maximum Temperature for Safe Use, deg. Cent.			Other Media for Which Recommended	Typical Applications	Alloy
Temperature Range, deg. Cent.	Coefficient (per 1° C.)			Temperature, deg. Cent.	Conductivity (C. G. S. Units)		Temperature, deg. Cent.	Resistance, michrom per cu. cm.	Oxide Gas	Fuel Gas	Sulfur Gas			
20 to 100[a]	0.000010[a]	1495 to 1385	7.6	20[a]	0.096[a]	0.15 to 0.16[a]	25[a]	62[a]	760[a]	760[a]	760[a]	Alkaline liquors, foodstuffs, oxidizing acids, some organic acids, steam.	Machine parts such as pump and valve bodies.	No. 1
20 to 700[a]	0.000012[a]	....	....	100[a]	0.096[a]	....	700[a]	113[a]						
20 to 100[a]	0.000010[a]	1510 to 1370	7.6	20[a]	0.054 to 0.072[a]	0.15[a]	20[a]	65[a]	870[a]	870[a]	815[a]	Oxidizing acids, especially nitric, foodstuffs, sea water, alkaline liquors, steam.	Nitric acid plant equipment, valve trim, steam pump valves, castings for moderate temperatures and low stresses, such as grate bars.	No. 2
20 to 900[a]	0.000013[a]	....	....	....	....	....	700[a]	117[a]						
20 to 100	0 000010	1450 to 1350	7.5	20	0.064	0.15	25[a]	68[a]	1035 to 1175	980 to 1150	980 to 1150	Foodstuffs and alkaline liquors, fumes of volatile heavy metals, oxidizing acids, mine waters, and of especial value in sulfur-rich atmospheres at high temperatures.	Annealing boxes, lead pots, roasting furnace rabble arms, cement chutes, pump and valve bodies.	No. 3
20 to 1000	0.000013	....	....	100	0.064	....	1000[a]	118[a]						
20 to 100[a]	0.000018[a]	1490 to 1430	8.0	20[a]	0.074[a]	....	20[a]	86[a]	760 to 980	760 to 980	....	Sea water, sulfuric acid in wide range of concentration and temperature, mine waters, steam, high-sulfur oils, alkaline liquors.	Ship propellers, pump and valve bodies impellers, rayon-producing equipment, oil still header-box plugs.	No. 4
20 to 800[a]	0.000019[a]													
20 to 100[a]	0.000016[a]	1470 to 1400	7.8	20	0.063	0.12[a]	25[a]	74[a]	870 to 925[a]	760 to 925[a]	150 to 700[a]	Sea water, alkaline liquors, hot dilute or cold concentrated sulfuric acid, acid sulfates, cold oxidizing acids, mine waters, foodstuffs, organic acids.	Pots, retorts, pump and valve bodies equipment of chemical plants, paper mills and dairies, marine fittings, ornamental work.	No. 5
20 to 1000[a]	0.000020[a]	....	....	100	0.063	....	700[a]	118[a]						
20 to 100[a]	0.000016[a]	1470 to 1400	7.8	20[a]	0.058[a]	0.12[a]	20[a]	75[a]	870 to 925[a]	760 to 925[a]	150 to 700[a]	Alkaline liquors, hot dilute or cold concentrated sulfuric acid, acid sulfates, sea water, cold oxidizing acids, mine waters, foodstuffs, organic acids.	Pots, retorts, pump and valve bodies equipment of chemical plants, paper mills and dairies.	No. 6
20 to 1000[a]	0.000020[a]	....	....	....	....	....	500 to 800[a]	112[a]						

TABLE I.—

Alloy	Chemical Composition, per cent					Physical Properties								Machining Behavior	Welding Behavior
						At Room Temperature					At Elevated Temperature				
	Carbon	Chromium	Nickel	Manganese	Silicon	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Izod Impact Strength, ft-lb.	Temperature, deg. Cent.	Stress Producing 1 per cent Elongation in 10,000 hours	Stress Producing 1 per cent Elongation in 100,000 hours		
IRON-CHROMIUM-NICKEL ALLOYS (*Cont.*)															
No. 7	0.50	22.0	22.0	...	1.5	60 000 to 70 000	45 000 to 60 000	5 to 10	3 to 10	....	540[a] 595[a] 650[a] 705[a] 735[a]	13 000 to 25 000[a] 8 000 to 16 000[a] 4 000 to 9 500[a] 2 000 to 5 000[a]	16 250[a] .... 2 300[a]	Tough; slightly easier than 18-8.	Satisfactory.
No. 8	0.30	28.0	8.0	...	1.5	70 000 to 80 000	55 000 to 65 000	1 to 3	1 to 3	....	....	....	....	Tough; but more readily machined than 18-8.	Satisfactory, if subsequently heat treated.
No. 9	0.30	26.0	16.0	...	1.5	....	....	....	....	....	....	....	....	Intermediate between 18-8 and 28-8 alloys.	Satisfactory.
No. 10	0.50	18.0	36.0	...	2.0	60 000 to 70 000	40 000 to 55 000	1 to 8	2 to 10	....	....	....	....	Similar to annealed high speed steel.	Satisfactory
NICKEL-RICH ALLOYS															
No. 11	0.60	13.0	62.0	1.0	1.5	60 000 to 75 000	35 000 to 45 000	1 to 5	1 to 5	....	540[b] 650[b] 760[b]	12 000[b] 9 000[b] 5 500[b]	....	Similar to annealed high speed steel.	Satisfactory.
No. 12	0.40	20.0	64.0	1.5	1.5	50 000 to 70 000	40 000 to 50 000	1 to 3	1 to 3	....	....	....	....	Similar to heat treated simple steels but at lower speeds and feeds.	Satisfactory.

[a] Data on the wrought alloy.
[b] Data on cast alloy containing 3 per cent tungsten.

Continued.

Coefficient of Thermal Expansion				Thermal Conductivity		Specific Heat	Specific Electric Resistance		Maximum Temperature for Safe Use, deg. Cent.			Other Media for Which Recommended	Typical Applications	Alloy
Temperature Range, deg. Cent.	Coefficient (per 1° C.)	Melting Temperature, deg. Cent.	Specific Gravity	Temperature, deg. Cent.	Conductivity (C. G. S. Units)		Temperature, deg. Cent.	Resistance, michrom per cu. cm.	Oxide Gas	Fuel Gas	Sulfur Gas			
20 to 100 20 to 1000	0.000016 0.000019	1415	7.9	20	0.052	....	20	90	1150	1100	....	....	Grids, hearth plates, rollers, rails, chains, containers, etc., in heating furnaces not carrying gases with high sulfur content, apparatus for hydrogenation of refinery waste gases.	No. 7
20	0.000014	1500 to 1400	7.9	20	0.025	....	....	....	1100	1100	1000	Mine waters, sulfur-rich atmospheres at high temperatures, nitric and other oxidizing acids.	Roasting furnace rabble arms, oil still tube supports, pump parts for hot oil in refineries, steel mill soaking pit dampers.	No. 8
20 to 100 20 to 1000	0.000015 0.000018	....	7.9 ...	20	0.039	0.14	20 700	80 117	1150	1150	180 to 1150	Mine waters, sulfurous acid and sulfite liquors, mixed acids, oxidizing acids, high-temperature atmospheres of moderate sulfur content.	Furnace hearth plates, cement kiln parts, recuperators, stack dampers, coal distillation retorts.	No. 9
20 to 100 20 to 1000	0.000014 0.000018	1485 to 1400	8.0	20	0.027	0.11	20	118	1000 to 1100	1000 to 1100	....	Sulfuric acid in wide range of concentration and temperature, alkaline solutions, fused alkalies to 900° C.	Grids, hearth plates, rollers, rails, chains, containers, etc., in heating furnaces not carrying gases with even moderate sulfur content, rayon-producing equipment, ceramic furnace parts, carburizing boxes.	No. 10
20 to 100 20 to 1000	0.000012 0.000016	1400 to 1260	8.1	20	0.033	0.14 (20 to 1000° C.)	20	108	800 to 1150	800 to 1150	....	Synthesizing ammonia, sulfuric and hydrochloric acid in some concentrations and temperatures.	Carburizing containers, oil-burner parts, special glass molds, chemical reaction chambers.	No. 11
20 to 100 20 to 1000	0.000013 0.000017	1440 to 1250	8.0	20	0.033	0.11	20	124	1100 to 1260	1100 to 1260	....	Fused alkalies and chlorides to 1000° C.	Carburizing containers, oil-burner parts, containers for fused alkalies and cyanide, resistance grids, boiler baffles, enameling racks, pyrometer tubes.	No. 12

cast, it is practically unmachineable, but with suitable annealing treatment a degree of machineability may be established.

Iron-Nickel Alloys:

Alloys principally of iron and nickel no longer find very extended use. Those containing 25 to 33 per cent nickel, frequently with 1.5 per cent manganese or 1.0 per cent silicon or 2.0 per cent chromium, at one time in use for contact with weak sulfate solutions, sea water, etc., have fallen out of favor during the past decade, due to the introduction of iron-nickel alloys high in chromium.

Iron-Chromium-Nickel Alloys:

It is in considering combinations of the latter type that one observes practically the entire corner of the ternary diagram from 7 to 40 per cent chromium and from 0 to 40 per cent nickel (alloys which by slight stretch of the imagination may still be called steels) to have been commercially exploited and applied with considerable success. This large number obviously makes difficult the selection of representative alloys through which to describe the group; hence all readers are not expected to agree with the seven chosen.

The first to be described, alloy No. 4, Table I, is one of the older of the corrosion-resisting alloys and contains less chromium than any of the others regularly manufactured at this time.

An important feature of the properties of this alloy is the strength at elevated temperatures, in which respect there is sharp differentiation from the plain chromium steels. Although the 18-per-cent chromium steel is so valuable because of surface stability in contact with oxidizing acids at low temperatures, and air and some furnace gases are moderately elevated temperatures, and the 28-per-cent chromium steel is equally valuable for exposure to oxidizing gases and to sulfur-rich atmospheres at very high temperatures, it is possible to stress them only lightly when hot, if flow and failure are to be avoided. They are not very tough at room temperature. The high-nickel iron-chromium alloys afford improvements in these respects that are most desirable; they are not totally free of objectionable or troublesome properties but they greatly assist in meeting conditions otherwise difficult to master.

The low-chromium high-nickel alloy just discussed possesses another property of particular industrial interest. Oil refineries experience considerable difficulty in maintaining header plugs in 18 per cent chromium, 8 per cent nickel steel tubes, in that the plugs have either too low a thermal expansion coefficient and loosen on temperature lowering, or have too nearly similar or too high a coefficient, and "freeze" in position, tearing the tube upon removal. This 20 per cent nickel, 8 per cent chromium steel possesses a coefficient just sufficiently low to avoid both troubles.

The so-called "18-8" composition has proved to be one of the most popular of the corrosion-resisting steels, largely because of its toughness and surface stability in contact with many natural and artificial substances. In the cast form, the higher carbon type has been used almost exclusively and has characteristics as shown in Table I (alloy No. 5).

The strength at elevated temperatures is a noteworthy feature, but the alloy has a shortcoming for this purpose which has given rise to much controversy and study. As cast, the alloy contains free carbides, and for maximum resistance to corroding substances these must be dissolved and retained in solution by quenching from about 1100 to 1150° C. But long exposure within the range of 475 to 775° C. causes an intergranular precipitation, of a phase generally regarded as a chromium-rich carbide, the result being lowered ductility and rather rapid intergranular attack in the presence of corrosives. Failure to apply the above quenching treatment appears to aggravate the condition, while the incorporation in the alloy of titanium to the extent of 5 times the carbon content, or of vanadium equal to ten times the carbon content, or of about 1.5 per cent copper and 1.5 per cent molybdenum, have been stated to overcome the deterioration, or at least to very markedly reduce it. In advance of corrosive attack, the embrittlement may be largely corrected by reheating to about 870° C., but can be fully removed only by quenching from about 1100° C. These treatments will not, however, prevent a recurrence upon reexposure in the precipitating range.

This composition does not include sufficient nickel in proportion to the chromium to render the metal totally unserviceable in the presence of sulfur-containing gases, but it is noteworthy that published maximum temperatures at which it may thus be exposed with safety, are not in close agreement. This may be due to the fact that oxidizing sulfur gases and reducing sulfur gases react with metals quite differently, as do wet and dry sulfur compounds. These are very important facts to consider in the selection of materials, so that where conditions are variable or not precisely known and tests cannot satisfactorily be made, it may be desirable to employ, initially at least, alloys of practically no nickel content.

Improvements in the so-called "18-8" alloy have been effected by the addition of elements other than those affecting the intergranular deterioration. Molybdenum in amounts up to 4 per cent improves resistance to sulfuric acid, sulfates, and other compounds, while tungsten in like amount greatly raises the load-sustaining capacity. It is of interest that this tungsten addition is effective only in the presence of both the nickel and the chromium and a certain amount of carbon, slightly greater than that shown in the table. While it is known that high-temperature strength in many of the alloys discussed in this paper, increases with increase in carbon up to about 0.4 per cent, excellent design strength and service experience up to 1000 to 1100° C. have been recorded for an alloy of 20 per cent chromium, 8 per cent nickel, 1 per cent carbon, and 1 per cent aluminum. Another alloy of interest contains 20 to 22 per cent chromium with 10 to 12 per cent nickel and was likewise developed to broaden the high temperature uses of alloys of this type.

As available data tend to show that intergranular deterioration decreases with a decrease in carbon content, there has been a growing demand for both wrought and cast products of the above "18-8" composition with not over 0.07 per cent carbon. Its production requires not only the greatest care in the selection of raw materials but in melting and refining details as well, and as the metal is sluggish in pouring, the oxide skin problem, previously noted, is very acute. In spite of the lesser degree of susceptibility to precipitation of carbides, it is advisable to exercise the same precautions, and castings are therefore treated in the same manner—water quenched from 1150° C. The properties shown in Table I, alloy No. 6, are quite like those of the higher carbon type.

One of the strongest of the ternary alloys, alloy No. 7, contains somewhat higher chromium and an equal amount of nickel. Its strength properties at elevated temperatures are excellent although not too well established, but the closely related group of compositions which it represents are finding rapidly increasing favor, through success in use. It is subject to intergranular deterioration at low visible temperatures to a much lesser degree than the "18-8" type even when the carbon content is higher, but its greatest use is at temperatures above the embrittling range. It is, however, quenched from about 1100° C. prior to use and possesses the properties shown in Table I.

A modification of the type just cited contains 3 per cent silicon, 1 per cent molybdenum and 0.4 per cent copper, and shows approximately the same room-temperature properties. By annealing, however, the elongation and reduction of area may be increased to over 30 per cent, but only by lowering the yield point to 25,000 to 30,000 lb. per sq. in.

Improvement of the 28-per-cent chromium steel has resulted in one of similar chromium content with 8 per cent of nickel, alloy No. 8, Table I. Characterized by a consistently smaller grain size and hence superior low-temperature toughness necessary in the operation, for example, of certain ore-roasting furnaces, it does not differ noticeably from the plain chromium-iron alloy in its behavior toward oxidizing gases and sulfur-bearing gases at very high temperatures. Though less susceptible to precipitation troubles and not requiring heat treatment when intended for high-temperature use any more than does the binary alloy, it is frequently, but not always, annealed in a similar manner.

A further increase in nickel content with only slight change in chromium has been responsible for a group of alloys represented by alloy No. 9, Table I. Within this group the nickel and chromium contents differ by as much as 4 per cent. These alloys are tougher at both room and high temperatures than the preceding alloy, but less useful in the presence of gases rich in sulfur. They generally require no heat treatment prior to use.

Among castings for very high temperatures, alloy No. 10, Table I, is commercially supreme, it having been estimated to account for 70 per cent of the total production for this class of service. Developed as a result of further desire for cost reduction of the 80 per cent nickel, 20 per cent chromium alloy (the first step was represented by 65 per cent nickel, 20 per cent chromium, balance iron plus small amounts of carbon, silicon, etc.), it was soon shown to possess improved strength and oxidation resistance at heat treatment temperatures. The high nickel content, of course, precludes its use in the presence of very much sulfur, but imparts ability to withstand a great degree of temperature and stress variation.

Nickel-Rich Alloys:

Finally it is desired to mention the two nickel-rich alloys of the ternary system, alloys Nos. 11 and 12, Table I, of which the one higher in chromium, alloy No. 12, is usually regarded as superior, due to greater oxidation resistance. Compared with all of the alloys described in this paper, they are claimed to show maximum ability to withstand the effects of frequent and rapid heating and cooling. But these types, to a greater degree than any of the others, as a result of their much higher nickel content, develop in the presence of sulfur compounds what has been called "corrosion embrittlement," a penetration of a chemical reaction along the grain boundaries. They are often considered as providing, in the absence of sulfur, the most economical heat treating containers. With sulfur present, supremacy is yielded to either the 18 per cent chromium, 36 per cent nickel alloy, or to the 28 per cent chromium, 8 per cent nickel alloy, depending upon conditions. But none of these alloys or any other previously noted is satisfactory for containers for molten tin or tin-rich alloys. For this service a suitable product remains to be developed.

A few other combinations of somewhat similar composition and application may be mentioned very briefly. Among these are to be noted an alloy of 60 per cent nickel, 25 per cent chromium, and 8 per cent copper, now widely applied in chemical plants for very strongly corroding solutions. Another containing 58 per cent nickel, 14 per cent chromium, 17 per cent molybdenum, and 5 per cent tungsten is especially useful for handling hydrochloric acid up to 70° C. but is applicable also in the presence of sulfuric acid at moderate temperatures, and, like the nickel-chromium-copper alloy, in oxidizing and reducing atmospheres up to 1000° C. Certain other nickel-base alloys are employed in competition with all those mentioned in this paper, but as they contain only one of the elements of the ternary system initially described, they are considered beyond the scope of this presentation.

MANUFACTURING PRACTICES

Other than the extreme care required in every operation, production methods for all of these alloys do not differ greatly from those in use in foundries producing simpler steels. The size of most orders being relatively small, melting units of small size are in practically universal use. This circumstance, combined with the difficulty of regulating alloy losses and controlling the degree of deoxidation, has made the open-hearth furnace an unsatisfactory medium, and has restricted production to electric arc and electric induction furnaces. Acid linings and slags have been used to some extent, but present too many objectionable features. They afford ease of melting and of maintaining a hot bath in a fully deoxidized state, thus eliminating many troubles that result from inability readily to attain these ends, but carbon and silicon pick-up are rapid and chromium control is very difficult. Basic practice is therefore most common in the arc furnaces, and while, obviously, the details cannot be discussed here, it should be noted that a large proportion of the total production is made in this manner, giving excellent control of composition and soundness.

The coreless induction furnace is of course a melting medium only, refining practices for its use not being developed commercially, but small size and simplicity of temperature and composition control have overcome the objection of high initial cost, and installations are multiplying rapidly. Some acid linings are in use although the greater number are basic.

Casting troubles are similar to those encountered in simple steels but are much more intense, being aggravated by high shrinkage and low thermal conductivity. Silicon up to 1 to 3 per cent in the various alloys increases fluidity, and being frequently beneficial to the properties of the products, is much used. Carbon adds to the fluidity but widens the melting range, and is objectionable in some products. High manganese, up to 2 per cent, is often used to improve soundness, but in some alloys is not desired. While patternmaker's shrinkage is generally stated as $\frac{3}{16}$ to $\frac{1}{4}$ in. per ft., there would be greater value to the foundryman in knowledge of the volume changes from pouring temperature to liquidus, from liquidus to solidus, and from solidus to room temperature. This may some day be available for all industrial metals.

SUMMARY

There will have been observed in the quoted data many instances of lack of agreement, such as wide ranges of creep-stresses at elevated temperatures, ranges of recommended maximum temperatures, etc. In some instances lack of numerical values indicates that no published information has been available, while in other cases values in print have been so obviously at variance with other known facts that they could not be safely included. A few instances have been noted of recommendations in favor of the use of high-nickel alloys at high temperatures in the presence of gases rich in oxidizing sulfur compounds. This has been discussed earlier in some detail. The entire summary points to a lack of information of high merit and indicates the need for more thorough experimentation and more careful recording of conditions and results in practical trials.

A few broad generalizations seem justified. Low-carbon and low-silicon castings, more particularly the former, are a tax upon the foundryman's facilities and the best materials available for his use. Design must be cooperative. The chromium steels are well suited to resist oxidizing acids, oxidizing gases, and sulfur-rich gases, at high temperatures, but are unsuited to high stresses at high temperatures or to numerous and sudden variations in stress or temperature. The high-nickel iron-chromium alloys are unsuited to sulfur-rich gases at high temperature but may be satisfactory at moderate temperatures with reduced sulfur compounds. They are valuable for resisting great stress at high temperature and sudden changes in stress and temperature. Some of these alloys are almost immune to oxidizing acids and are very satisfactory in sulfuric acid, while others possess oxidation resistance to a greater degree than the plain chromium steels. In fact, practical trials under very severe conditions indicated a number of years ago that a medium-carbon, silicon-containing alloy having about equal proportions of iron, chromium, and nickel was the most satisfactory one from the viewpoint of both strength and stability. Experimental evidence seems about to confirm these findings.

Failures of these various highly alloyed castings may occur from either chemical or mechanical causes. Severe surface attack is of course the result of incorrect alloy selection for the conditions of use. Mechanical failure may be due to poor design, the use of an alloy of unsatisfactory strength or ductility at the temperature of use, true fatigue, abuse in heating and cooling, change in the properties of the alloy as a result of microstructural changes due to long exposure at temperature, or to defects of foundry origin. All can be corrected by enlightened effort.

Acknowledgment:

No specific references have been made in this paper to other articles from which data have been obtained, but acknowledgment is here made of the valuable collections represented by the work of Committee A-10 of the American Society for Testing Materials[1] and the Symposium on the Effect of Temperature on the Properties of Metals[2] as well as many other isolated articles. Thanks are due Mr. A. C. Jones of the Lebanon Steel Foundry for mechanical test values on stainless-iron castings and Mr. H. D. Newell of the Babcock & Wilcox Tube Co. for criticism of the manuscript and the provision of considerable data.

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[1] See tables on "Chemical Compositions, Physical and Mechanical Properties and Corrosion-Resistant Properties of Corrosion-Resistant and Heat-Resistant Alloys," prepared by the A.S.T.M. Committee A-10 on Iron-Chromium, Iron-Chromium-Nickel and Related Alloys, *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part I, Insert Plates V to XV (1930).

[2] Symposium on Effect of Temperature on the Properties of Metals, published jointly by the American Society for Testing Materials and The American Society of Mechanical Engineers (1931).

DISCUSSION

MR. N. B. PILLING[1] (*presented in written form*).—In discussing this excellent outline of the heat- and corrosion-resistant casting alloys, I should like to draw attention to a few points of general interest.

Mr. Strauss' comments on laboratory corrosion tests are directed, I feel sure, to attempts to forecast by short-cut methods and arbitrary simplifications, the performance of untried materials under the complex conditions which prevail with corrosion at very high as well as ordinary temperatures. To this we must agree, but so complicated are these service conditions that metallurgical development would have a task indeed, were it faced with the necessity of depending entirely upon hard experience for guidance. Laboratory tests carefully arranged and executed have their proper place, both in the evolution of alloy materials and in the analysis of disappointing applications. Such simplified studies, economizing effort through the selective emphasis of certain aspects, can be made to hasten progress even in hard cases like these, by cutting through unessentials and letting the searching test of service be aimed in fruitful directions. There is, however, a double responsibility involved: it should be as great a sin for the engineer to make carelessly broad inferences from limited tests as for the experimentalist to concentrate his attention mistakenly upon the wrong properties!

The heat-resisting alloys of the general type described give a striking example of a development in which practical application has sped far ahead of scientific investigation, a fact reflected in the baffling nature of some of the difficulties associated with their use. Susceptibility to damaging corrosion by gases, particularly those containing sulfur, rightly excites general interest, and as brought out repeatedly in the paper, may be sufficiently critical to bar the use of an otherwise desirable material. The popular conception of susceptibility to sulfur, or at least the one which is often repeated, is the view taken by the author, that heat-resisting alloys containing more than very moderate contents of nickel are quite unserviceable in the presence of even slight proportions of sulfur. Yet it is a curious fact that detailed accounts of the nature of this unserviceability for the several common types of alloys are almost wholly lacking.

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[1] Metallurgist, International Nickel Co., Bayonne, N. J.

It would be a considerable service to those interested in the further development of heat-resisting alloys if the author would enlarge upon this difficulty in the use of the iron-chromium-nickel alloys. The highly damaging and penetrating nature of sulfur corrosion upon nickel and the nickel-rich alloys of low chromium content probably suggests the occurrence of this action to a diluted degree with alloys in which the nickel content is much reduced. But recent studies into this question in some detail indicate that the analogy cannot be carried very far, owing to an important change which occurs in the nature of the sulfide coating. When sufficiently rich in nickel, this has a low melting point and in the molten condition is not only wholly unprotective but stimulates intercrystalline penetration. A rise in either iron or chromium content raises this critical fusion temperature to an extent which may, with some proportions of these elements, considerably exceed the temperature at which these alloys are customarily used. Under such conditions—that is, temperatures and composition appropriate to insure a solid sulfide coating—the destructiveness of sulfur is greatly reduced, and when comparisons are made with alloys constant in chromium content, the presence of considerable percentages of nickel is not found to increase attack even by highly sulfurous gases. Resistance to sulfur would thus seem to be a question, not simply of the presence or absence of nickel, but of its suitable proportioning to chromium and iron.

MR. A. C. JONES[1] *(presented in written form)*.—Mr. Strauss has mentioned the desirability of proper engineering design in the procurement of satisfactory castings. This point should be strongly emphasized. There has been a lack of appreciation of the influence of good casting design in the past with respect to the manufacture of high quality plain carbon and low-alloy steel castings. Designing engineers are more and more seeking the advice of the foundry, with mutual advantage. It is doubly imperative, in casting the more expensive corrosion-resistant alloys, with their peculiar pouring and solidifying characteristics, that the closest cooperation be maintained. No matter how good the metal is metallurgically, a shrinkage defect may shorten the life of the casting. If detected, and the casting is scrapped in the foundry, naturally the cost of the job is increased, to say nothing of the delay in delivery to the customer, which is of paramount importance. But if the defect is discovered at the plant of the purchaser or in the field, it is even more serious.

A problem facing the alloy steel foundries is the great number of compositions requested by consumers. Sometimes a very special analysis is necessary; and as Mr. Strauss has stated, the conditions of service must be carefully analyzed prior to a proper recommendation, preferably after a service test. But in many cases standard alloys offered by the foundry, with which it is more familiar, would serve equally well and might produce a better all-round casting. Here again is opportunity for teamwork between the metallurgists representing buyer and seller.

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[1] Research Engineer, Lebanon Steel Foundry, Lebanon, Pa.

Turning now to the data in Mr. Strauss' paper, the physical properties reported for elongation and reduction of area for the 18 per cent chromium, 0.12 per cent carbon alloy may not be applicable to castings, which, because of light sections in some part, must be poured with very hot metal. This metal, because of low carbon content, is very sluggish, so that it must be raised to a high temperature for fluidity. In doing this the grain structure is coarsened considerably, so that very little ductility remains. Heat treatment is ineffective in refining the structure. A slightly higher carbon content gives a better casting and in many cases is equally as satisfactory from a corrosion standpoint.

Mr. Strauss mentions the machining behavior of the 28 per cent chromium, 0.50 per cent carbon steel as being the same as medium carbon steel, which would indicate about the same machineability for it as the 13 per cent chromium and the 18 per cent chromium stainless irons. Our experience has been that the 28 per cent chromium alloy machines more like cast iron than medium carbon steel, and is the most readily machined material of the corrosion-resistant alloys.

Referring to the tensile properties of the 18 per cent chromium, 8 per cent nickel alloy, if the carbon content is close to 0.15 per cent we have found that the yield point will average 35,000 lb. per sq. in. and the tensile strength about 75,000 lb. per sq. in. With carbon around 0.07 per cent, the yield point will be about 25,000 lb. per sq. in., and the tensile strength around 68,000 lb. per sq. in.

The tensile properties of the 28 per cent chromium, 8 per cent nickel alloy reported show very low values for elongation and reduction of area; namely, 1 to 3 per cent for both characteristics. We have found an alloy of practically the same analysis, but having a nickel content of 11 per cent, averages 15 per cent for elongation and 10 per cent for reduction of area.

MR. J. A. PARSONS, JR.[1] (*presented in written form*).—The selection of the proper composition of special steel castings for corrosion-resistant applications in the chemical and allied industries is by no means a simple task. A systematic correlation of these alloys such as the author of this paper has presented is an invaluable contribution to industry. A description of many of the problems confronting the producer of these steels is useful information in the hands of the chemical engineer in preparing specifications which differ so widely from those for plain carbon steel castings.

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[1] The Duriron Co., Inc., Dayton, Ohio.

There are, however, one or two instances which are not quite clear in connection with the specific application of these various mixtures in regard to corrosion resistance. Under the description of the 18 per cent chromium, 8 per cent nickel steel, mention is made of the fact that this material is recommended for hot dilute sulfuric acid. The same thing is brought out in connection with the same steel with carbon under 0.07 per cent. It has been our experience that high nickel contents considerably in excess of 8 per cent are necessary for resistance to dilute sulfuric acid, especially when hot. In other words, a composition similar to one mentioned, containing 22 per cent nickel, or a composition containing 36 per cent nickel and 18 per cent chromium, also mentioned, would be much more satisfactory for this type of service.

Very often in practice, the dilute acid is contaminated with various salts of the heavy metals. Some of these have reducing properties while some are highly oxidizing. In the latter instance, high chromium is necessary in order to build up stable surface films. In other words, it requires both high chromium and high nickel in order to resist hot dilute sulfuric acid under all conditions and it also is very important to reinforce this alloy with both silicon and copper. Care must be exercised in making copper additions, to have sufficient nickel to insure complete solution of the copper, otherwise corrosion resistance is very severely impaired.

The generous use of silicon is especially advantageous in promoting fluidity in the foundry, and it is possible to successfully increase this element to as high as 3 per cent without impairing the ductility.

The author has demonstrated the deleterious effect of nickel in connection with corrosion-resistant alloys intended for use in connection with sulfur bearing gases. This I believe is very true, and would probably preclude the use of a standard mixture for castings intended for service in either hot dilute sulfuric acid or sulfur bearing gases. This brings again to mind the fact that no single corrosion-resistant steel can hope to cover a large majority of the problems encountered in practice, and that it is necessary to study each problem in detail before making specific recommendations.

It has been demonstrated beyond possible doubt that molybdenum in the high nickel chromium steels is beneficial in so far as resistance to phosphoric, acetic and hydrochloric acids are concerned, but it is doubtful if this element contributes anything towards sulfuric acid resistance.

MR. C. E. MACQUIGG.[1]—Mr. Strauss shows the silicon content of all the alloys as uniformly one per cent or more (he did state that these were nominal contents only), but it is a fact that a great many of these alloys are produced with silicon less than 0.5 per cent.

One thought was brought to mind by the reference to the strengths at high temperatures, namely, that information on this subject is being gathered by a number of laboratories independently, and particularly by laboratories working under the coordination of the Joint Committee, of the A.S.M.E. and A.S.T.M., on Effect of Temperature on the Properties of Metals. However, that information is going to be some time in forthcoming. Those of us who are working on that committee realize the necessary slowness with which these experiments can be performed. I hope that the Society realized fully the extra efforts being made by the Joint Committee on creep testing. We are able to say that we are rapidly reaching our objective in several lines.

MR. J. T. MACKENZIE.[2]—I should like to point out that the successful use of heat-resistant materials depends to a considerable extent on the uniformity of heating. We tried 7-per-cent plain chromium steel, 18 per cent chromium, 8 per cent nickel and 28 per cent chromium, 18 per cent nickel alloy in a certain hot blast cupola casting (approximately 8 ft. long) and they all failed by warping and pulling loose from the upper connection. (An illustration of the type of casting appears in Fig. 1 of a paper on "The Moore Hot Blast Cupola," appearing in the *Transactions* of the American Foundrymen's Association, Vol. II, No. 8, August, 1931, p. 197.) The plain chromium castings were as thick as the cast iron which they replaced, but the high-alloy castings were only 60 per cent of the thickness of the cast iron. Cast iron, approximating ingot mold analysis, gave 100 heats, the plain chromium 50 and the other two compositions 4. Undoubtedly if even heating and cooling were possible, the alloy castings would be far superior.

MR. JEROME STRAUSS[3] (*author's closure*).—All of these several discussions are very much appreciated. The data submitted by Mr. Jones afford an indication of the wide differences in properties which may be obtained at the present time by different manufacturing practices used in different foundries. I have seen a number of tension tests made at room temperature on 18 per cent chromium, 8 per cent nickel castings of both the 0.07 per cent maximum carbon and 0.16 per cent maximum carbon types which showed practically identical properties in the two, the differences being only of the order of the variation between duplicate tests.

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[1] Manager, Union Carbide and Carbon Research Laboratories, Inc., Long Island City, N. Y.

[2] Chief Chemist, American Cast Iron Pipe Co., Birmingham, Ala.

[3] Chief Research Engineer, Vanadium Corporation of America, Bridgeville, Pa.

The comments of Mr. MacQuigg with regard to silicon content are very important, perhaps more important in the case of the alloys of chromium and iron than in the case of those containing also an appreciable amount of nickel. Silicon has its utility in increasing the ease of casting. It also imparts improved resistance to oxidation at elevated temperatures. However, in the case of the high chromium alloys it promotes coarse grain size and consequent brittleness, more particularly at room temperature but to some degree at high temperatures also. This fact is closely associated with the comments which Mr. Pilling made concerning the relationship between nickel and chromium in these alloys and their behavior in the presence of sulfur compounds. Perhaps the matter is best illustrated by describing an instance with which I have had close contact. The problem concerned the use of rabble arms in a roasting furnace operating at different times at temperatures between 1300 and 1800° F. (705 and 980° C.) in the roasting of an ore very rich in sulfur. The 28 per cent chromium alloy, if containing under one per cent silicon, was sometimes satisfactory, but gave variable performance. All of the castings showed satisfactory resistance to oxidation and other corrosion, and were amply strong at the operating temperature. Some, but not nearly all, were effective if the furnace was rotated in the cold after charging. On the other hand, castings of the same chromium and carbon contents containing about two per cent silicon were entirely unsatisfactory if operation in the cold was attempted. At high temperatures, howeven, they also were serviceable. The use of a 28 per cent chromium, 8 per cent nickel alloy was eminently satisfactory, either hot or cold; in relation to the chromium content, the nickel content was sufficient to impart toughness at both low and high temperatures but insufficient to be productive of troubles from sulfur gas corrosion. In the presence of these sulfur gases, the 18 per cent chromium, 8 per cent nickel alloy was not usable because of the lower chromium to nickel ratio; trouble resulted from both oxidation and sulfur corrosion. The 28 per cent chromium, 16 per cent nickel alloy was also quite unserviceable at high temperatures, the nickel content being too high for the amount of chromium present; corrosion progressed rapidly. This experience illustrates the effective oxidation resistance of the 28 per cent chromium steel, the production of room temperature but not high-temperature brittleness by a high silicon addition, the permissibility of 8 per cent nickel in the alloy when exposed to sulfur-rich gases, if the chromium content is very high, and the ineffectiveness under these conditions of higher nickel content steels.

(*Author's closure by letter*).—Having had an opportunity to review more closely Mr. Pilling's comments, it appears that his statement that I have expressed the view that "heat-resisting alloys containing more than very moderate contents of nickel are quite unserviceable in the presence of even slight proportions of sulfur" is not correct. It is clearly stated in the paper that the 18 per cent chromium, 36 per cent nickel alloy is serviceable in the presence of low sulfur concentration in some gas mixtures, and that the 28 per cent chromium, 8 per cent nickel alloy is eminently satisfactory in many sulfur-rich atmospheres. The further distinction between the effect of oxidizing and reducing conditions is also stated therein. Nevertheless, a clearer understanding may result from the details given in my verbal discussion. Mr. Pilling's views on the designing of laboratory tests, the value of the data thus secured, and the relation of this data to service performance, do not differ essentially from those expressed in the paper.

Mr. Jones compares the machining behavior of the 28 per cent chromium steel to that of cast iron. Neither this description nor my original description is perfect, and while it is true that this very high chromium steel machines more readily than those of lower chromium content, it still produces chips which under given conditions more closely resemble those of medium-carbon steel.

Mr. Parsons' comments are timely. As he has indicated, behavior of metals in solutions containing free sulfuric acid is dependent in a very large measure upon the other substances present in the solution. None of the alloys discussed are totally immune to such solutions, especially when hot, and the recommendations of various manufacturers therefore frequently differ. Nevertheless, users whose problems involve the use of acid solutions will do well to study closely Mr. Parsons' comments.

The instance cited by Mr. MacKenzie very effectively confirms the statements in the paper dealing with the influence of high expansion rates in the presence of sharp temperature gradients.

AUSTENITIC MANGANESE STEEL CASTINGS

BY JOHN HOWE HALL[1]

HISTORICAL

Austenitic, or Hadfield's, manganese steel was invented in 1882 by Sir Robert A. Hadfield, who in that year made a series of steels containing manganese in amounts varying from 0.83 to 21.69 per cent. Specimens of these steels were exhibited and described by his father, Robert Hadfield, before the Institution of Mechanical Engineers in January, 1884, and subsequent to 1882 various British and United States patents were granted to Robert Hadfield, and later to Robert A. Hadfield, covering steels containing high percentages of manganese. The earliest technical report of this work is a paper by R. A. Hadfield in the *Journal* of the Iron and Steel Institute (British),[2] and a more circumstantial account is given in his recent book.[3]

At the time of its discovery this metal was looked upon as a metallurgical paradox, since it was the first steel known to man that was toughened and somewhat softened by quenching in water from a high temperature. It was non-magnetic whereas other known steels attracted the magnet, it exhibited great strength combined with remarkable toughness, it became intensely hard if severely cold worked, and in other ways it failed to behave like other ferrous metals. These peculiarities, of course, were due to the fact that manganese steel is an austenitic, rather than a pearlitic or a sorbitic, steel, as all ferrous metals then known were.

NOMENCLATURE AND COMPOSITION

During the last ten or fifteen years various pearlitic or sorbitic steels have been developed, containing manganese in amounts varying from 1 to 2½ or even 3 per cent, and a good deal of confusion exists as to the distinction between these steels and austenitic manganese steels. The pearlitic steels have been known sometimes as "intermediate-manganese steel," sometimes as "high-manganese steel," and, to make the matter still more involved, sometimes simply as "manganese steel," a term which to most metallurgists signifies the austenitic material. The tendency is toward the adoption of "intermediate-manganese steels" as the proper name of the pearlitic or sorbitic alloys, and though "intermediate" is a rather vague term, perhaps it is as well to adopt it in the place of some more definitely descriptive name, and to describe the Hadfield product as "austenitic manganese steel"—a term, at least, that leaves no room for misunderstanding, though it is rather an awkward phrase.

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[1] Technical Assistant to President, Taylor-Wharton Iron and Steel Co., High Bridge, N. J.

[2] R. A. Hadfield, "Manganese Steel," *Journal*, Iron and Steel Inst., Vol. II, p. 70 (1888).

[3] R. A. Hadfield, "Metallurgy and Its Influence on Modern Progress," Chapman & Hall, Ltd., London (1925).

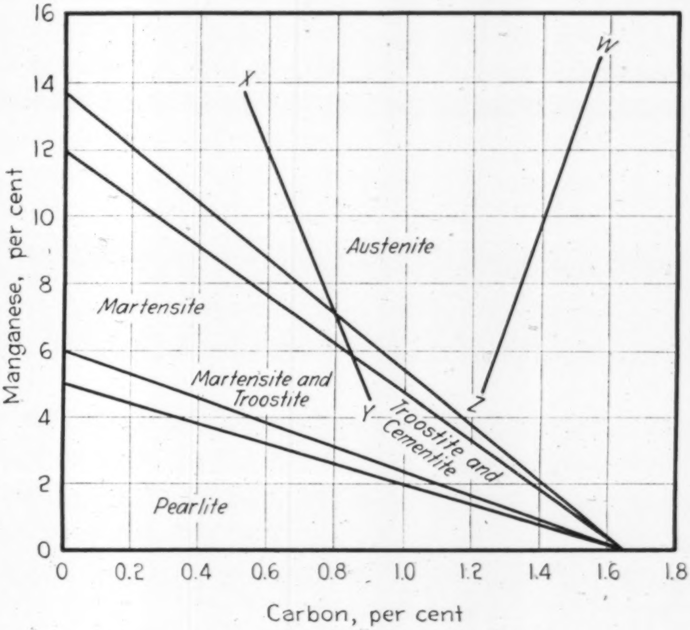

FIG. 1.—Constitutional Diagram of Manganese Steels (Based on the Work of Guillet).

By proper control of the carbon content, austenitic steels can be produced with manganese as low as 5 per cent, perhaps even as low as 4 per cent. Indeed, according to the heretofore accepted constitutional diagram of the manganese steels, based on the work of Guillet (Fig. 1), all compositions beyond the line connecting the points 14 per cent manganese and 1.65 per cent carbon in that diagram are austenitic. This diagram, however, is seriously deficient in several respects, and particularly in neglecting to take account of the presence of cementite in the steels containing carbon above about 1 per cent.

The lines *X Y* and *W Z* in Fig. 1 represent roughly the limits of composition within which lie the steels which can be made to consist of pure austenite by quenching in water from about 1060° C.[1] To the left of the line $X\ Y$ is the zone of martensitic steels, to the right of line $W\ Z$ the zone of steels containing free cementite after quenching. Between the lines $X\ Y$ and $W\ Z$ the steels in the cast condition or the annealed and slowly cooled condition contain amounts of cementite varying with the carbon content. The equations of these lines are as follows: For line $X\ Y$, $C = 1.075 - 0.04\ Mn$; and for line $W\ Z$, $C = 1.075 + \frac{0.1\ Mn}{3}$.

Though the steels whose compositions lie toward the point of this inverted triangle have many of the characteristic properties of the usual austenitic manganese steels, such as resistance to wear, hardening power, etc., yet less than 10 per cent manganese is seldom if ever used in austenitic steel. The reason for this is not, as has often been supposed, that a steel with, for instance, 8 or 9 per cent manganese is fatally weak, brittle, or deficient in resistance to wear, but is purely a practical result of the sort of service for which austenitic manganese steels are generally used. There is not a sudden, but a slow and gradual loss of strength and toughness, and little if any decrease in wear resistance, as the manganese content is decreased, and for some uses it will probably eventually be found that steels of 8 and 9 per cent, perhaps even of 5 and 6 per cent, manganese are perfectly satisfactory. In the majority of applications in which austenitic manganese steels are used today, however, the dimensions of the parts and the unit stresses to which they are subjected are based upon the properties of the stronger and tougher steels containing over 10 per cent manganese. Efforts to substitute steels of lower manganese content without change of design have generally failed, because the castings broke under the stresses to which they were subjected in service; but it is quite possible that somewhat heavier sections of the weaker steels would give as good service as light sections of the more expensive metals now used.

As usually produced, the composition of austenitic manganese steels lies within the following limits:

Carbon, per cent	1 to 1.40
Silicon, per cent	0.30 to 1.00
Manganese, per cent	10 to 14
Sulfur, maximum, per cent	0.04
Phosphorus, maximum, per cent	0.10

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[1] See paper by John Howe Hall, "Manganese in Cast Steels," *Proceedings*, Am. Foundrymen's Assn., Vol. XXXIV, p. 1153 (1926).

Some makers keep the lower limit for manganese at 11 per cent, feeling that the steels containing from 10 to 11 per cent manganese are more liable to breakage under heavy stresses than those with more than 11 per cent. The tendency is to hold the carbon to a maximum of 1.30 or even 1.25 per cent, because the heavier castings tend to crack in heat treatment if the carbon exceeds 1.30 per cent. To secure a carbon content below 1 per cent requires the use of very expensive manganese alloys, containing lower percentages of carbon than commercial ferro-manganese, and for most uses the lower carbon steels have no advantages over the ordinary product.

Silicon in amounts up to at least 1 per cent promotes fluidity of the steel, and thereby makes it easier to pour intricate castings, and the silicon has no harmful effect upon the steel. Indeed, some of the leading makers believe that silicon up to 1.50 and even 1.75 per cent increases the wear-resisting qualities of the steel, and for certain sorts of service they make use of silicon above the usual upper limit of 1 per cent.

Sulfur in the austenitic steels is so low that it is seldom considered necessary to determine it, because much of the sulfur, originally present in the fluid steel, floats out as sulfide of manganese and is eliminated in the slag or by oxidation to SO_2. The phosphorus content of commercial ferro-manganese is such that as a rule the content of that metalloid in the finished steel lies between 0.070 and 0.100 per cent. Determinations by one maker indicate that phosphorus up to 0.125 per cent or slightly over has no harmful effect upon the strength, toughness, or wearing qualities of the steel.

MANUFACTURE

Austenitic manganese steel is made either in the basic electric furnace or by mixing in a ladle 80-per-cent ferro-manganese and low-carbon steel from an open-hearth furnace or a bessemer converter (bottom blown or side blown). The proportions of the metals used in the latter method are shown by the following calculation:

	Weight, lb.	Carbon, per cent	Carbon, lb.	Manganese, per cent	Manganese, lb.
Molten soft steel.........	5400	0.15	8.1	0.20	10.8
Molten ferro-manganese ..	1150	6.5	74.75	80.00	920.0
Manganese steel..........	6550	1.26	82.85	14.21	930.8

In thus combining molten open-hearth or converter metal with liquid ferro-manganese in the ladle, a considerable amount of manganese is lost in deoxidizing the soft steel, so that the analysis of the steel produced by the above mixture of metals will generally be not far from 12.5 or 13 per cent manganese and 1.25 per cent carbon.

The foundry scrap, in the form of heads, gates, and "waster" castings, can be reconverted to steel by the open-hearth or converter process, but only at the cost of the practically complete loss of the contained manganese. The basic-lined electric furnace is utilized for the conversion of the scrap with but small loss of manganese, the metallic charge to the furnace usually consisting of a mixture of ordinary steel scrap and manganese-steel scrap, with sufficient ferromanganese and silico-manganese to bring the analysis of the whole to the desired composition. The proportion of the different metals charged depends, of course, upon the amount of manganese-steel scrap available, and accordingly varies somewhat from time to time. Most of the foundries producing austenitic manganese-steel castings buy a certain amount of manganese-steel scrap in the market, and use it regularly as a part of their metallic charge in the electric furnace.

In the majority of locations, where power is available at a reasonable figure, the cost of manufacture in the electric furnace is lower than that by the open-hearth or converter method, especially when manganese-steel scrap can be economically utilized as part of the charge, and of late years the tonnage of manganese-steel castings made by the electric-furnace method has considerably exceeded that produced by the older processes.

The best informed opinion is that there is no difference in the quality of austenitic manganese steel produced by any of the commercial processes, as measured by the strength, toughness, resistance to wear, or any similar property. In particular, the electric-furnace process has not been found to produce a superior grade of product, because the three respects in which electric-furnace steel is supposed to exceed other steels in quality, freedom from sulfur, freedom from phosphorus, and freedom from oxides, do not apply to manganese-steel manufacture. The sulfur is so low in manganese steel made by all the processes as to be practically negligible; no elimination of phosphorus in the electric furnace is possible when manganese-steel scrap forms a part of the charge, so that the phosphorus in the steel made by all the processes is about the same; and the deoxidation due to the addition of some 14½ per cent of manganese to soft steel is probably as complete as that obtained in electric-furnace practice. Thus no superiority for any one process is to be expected, and it has been found by numberless laboratory tests, by shop experience, and by the one unanswerable test, that of service, that manganese steel made by any one of the commercial processes is indistinguishable from that made by the others.

HEAT TREATMENT

In the cast condition, manganese-steel castings are quite brittle, partly because of the presence of free cementite, breaking up the continuity of the structure of the steel, and partly because in cooling slowly from the heat of casting some of the austenite is partially transformed to troostite or martensite. To effect the solution of the cementite, and to fix the steel in the austenitic condition—and thereby render it strong and tough—the castings are heated to a temperature somewhat over 1000° C., generally about 1040 to 1060° C., and quenched in cold water. If the proper temperature is not attained before quenching, the solution of the cementite is incomplete, so that full strength and toughness are not secured. If the temperature of the castings is allowed to fall below a point that varies with the rate at which they are cooling, but lies between about 850 and 750° C., before they are quenched, cementite will fall out of solution, resulting in a weak condition and a considerable loss of ductility. To reheat the properly toughened castings for a long time at any temperature over 350° C., or for a short time at or over 400° C., liberates cementite in a multitude of thin sheets throughout the austenitic ground mass and renders the steel exceedingly brittle.

This embrittlement of austenitic manganese steel upon heating the quenched metal at low temperature makes it impossible to use a drawing heat to relieve the stresses set up in complicated castings by quenching. As may well be imagined, these stresses are severe and result in serious distortions of the castings and even in cracking and breakage unless the design of the parts is carefully controlled by experienced men. This problem is further complicated by the fact that the crystal structure and grain size of cast austenitic manganese steel are greatly affected by the temperature at which the steel is poured. A high pouring temperature results in a coarsely columnar crystal structure some 15,000 to 20,000 lb. per sq. in. lower in tensile strength than the equiaxed and comparatively fine-grained structure produced by pouring the steel close to its freezing point. At ordinary rates of cooling, austenitic manganese steel does not exhibit the critical point A_1, at which the austenite in ordinary steels transforms to pearlite, and therefore, when the steel is heated for quenching, it does not pass through this critical point. As a result, no grain refinement occurs in heat treatment, but the grain size remains what it was in the untreated castings. Naturally, hot metal is required to "run" light sections, so that a casting with a single light part must usually be poured "hot," regardless of the size of its other portions. Both the light and the heavy sections are then necessarily coarse-grained, and weaker than if the casting had been so designed that it could be poured at a lower temperature.

ELECTRICAL, MAGNETIC, AND THERMAL PROPERTIES

The electrical resistance of austenitic manganese steel is 71 microhms per centimeter-cube, or seven times that of pure iron;[1] the average thermal conductivity between 0 and 100° C. is 0.027 c.g.s. units or about one-sixth that of pure iron;[1] and the mean coefficient of expansion between 0 and 100° C. is 0.000018 per 1° C., or about one and a half times that of pure iron.[1]

To all intents and purposes the steel is non-magnetic, that is, it has no attraction for the magnet. Determinations of normal induction and magnetizing force, and of magnetic properties in intense fields, are quoted in detail in a paper by the author and G. R. Hanks in the *Proceedings* of the Society.[2]

The average user of manganese steel does not realize that the combination of a high coefficient of thermal expansion and a low thermal conductivity have a tremendous influence upon the design of manganese-steel castings, but the foundryman has to cope with this problem every day, often to his sorrow. Manganese steel castings are quite brittle before heat treatment, and excessive stresses, from whatever source, will crack or break them. The low thermal conductivity of the metal means that in cooling in the mold, light sections will cool much more rapidly than heavy ones, and the outside of heavy sections, much faster than the inside. In heating the castings before quenching, the reverse condition exists. These inequalities of heating and cooling rates result in unequal rates of expansion and contraction of the different parts of a casting, and these inequalities are about 1½ times as great in manganese steel as in soft steels. Naturally, such unequal expansion and contraction set up severe stresses, and these stresses will break the castings unless the relation of the thicknesses of the various parts is kept within proper limits. The same thing, of course, is true also of the stresses set up in quenching the castings in water, which are even more severe than those due to cooling in the molds or to heating before quenching. The severity of these quenching stresses is to some extent offset by the fact that they are set up after the steel has grown comparatively cold, and therefore has become toughened so that it is able to yield somewhat to the internal stresses, and hence to reduce them. None the less, many improperly designed castings of manganese steel crack in quenching, and in particular it is necessary to limit sharply the maximum thickness of sections of manganese steel castings, because it is practically impossible to quench pieces over 5 or 6 in. thick without cracking them. These cracks generally start at the center and extend toward the surface, and frequently do not show on the outside until the service stresses to which the castings are subjected have caused the cracks to spread, often with disastrous results.

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[1] R. A. Hadfield, "Metallurgy and Its Influence on Modern Progress," Chapman & Hall, Ltd., London (1925).

[2] John Howe Hall and G. R. Hanks, "Composition and Physical Properties of Cast 12-per-cent Manganese Steel," *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part II, p. 626 (1924).

PHYSICAL PROPERTIES

Manganese steel being commercially unmachineable, test specimens cannot be machined to size, but must be prepared by the slow and costly process of grinding. To save expense, many tension-test specimens of manganese steel are cast nearly to size and finished by grinding. However such a test specimen may be cast, it is not absolutely solid at the center, and the results secured from it are considerably affected by this fact. Tests of manganese steel made on bars ground from test specimens attached to heavy blocks or to castings in such a way as to be absolutely sound, such as are used for determining the properties of machineable cast steels, are few and far between. Such tests, of course, give an idea of the average properties of the steel in large sections, while the small cast-to-size tests represent fairly well the properties of the whole cross-section of light castings. In the following table are shown the usual static properties:

TYPE OF TEST SPECIMEN	TENSILE STRENGTH, LB. PER SQ. IN.	PROPORTIONAL LIMIT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT	BEND $\frac{1}{2}$ BY $\frac{3}{4}$ IN. ON 1-IN. PIN, DEG.
Cast to size........	80 000 to 110 000	......	15 to 35	15 to 35	180
Ground from coupon	118 800[a]	42 900[b]	44.1[a]	39.0[a]	...

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[a] Average of 15 tests.

[b] Average of 5 tests.

The considerable variation in the tensile strength in the above table is attributable largely to the influence of pouring temperature upon the grain size, which has already been described. The yield point of cast manganese steel cannot be determined by the "drop of the beam," because there is no point at which marked stretch begins to occur, but extension proceeds in a series of successive starts and stops of gradually increasing magnitude. The figures given in the above table are based upon careful measurements of elongation with an Olsen extensometer, and represent the point where the stress-strain curve departs markedly from a straight line. These determinations have seldom been made on specimens cast to size, so that figures are given only for the bars ground from specimens cast attached to heavy feeding blocks.

Miscellaneous physical properties, determined on various types of test bars, are given in the following table:

TYPE OF TEST SPECIMEN	LIMIT OF PROPORTIONALITY IN COMPRESSION, LB. PER SQ. IN.	SHEARING STRENGTH, SINGLE SHEAR, LB. PER SQ. IN.	FATIGUE LIMIT, LB. PER SQ. IN.
Cast to size....................	.....	84 000	.....
Ground from coupon............	24 000	.....	39 000

HARDNESS

The hardness of manganese steel is always a surprise to those not familiar with this sometimes perplexing material. In the cast condition the Brinell hardness value is slightly over 200; after heat treatment it is but slightly lower, averaging from 180 to 200, and variations in the heat treatment that cause wide differences in the strength and toughness affect the Brinell hardness very little. Only by prolonged annealing at and around 500° C., which changes the physical state of the steel completely,[1] can the hardness be greatly affected by heat treatment alone. This treatment, it may be remarked in passing, raises the hardness of the steel to well over 500 Brinell, and at the same time makes it quite strongly magnetic,[2] a little easier to machine, and very brittle.

The hardness of cast manganese steel, however, is increased tremendously by cold work; by pounding a single spot upon the surface of a casting with the pean end of a machinist's hammer, the hardness can be rapidly brought to over 500 Brinell. The author and F. F. Lucas of the Bell Telephone Laboratories have confirmed[1] the surmise of Howe and others that this hardening is due to the formation of martensite in the slip planes of the austenite crystals. In many types of service involving heavy wear in which manganese steel is used, the castings are subjected not only to wear, but also to severe pounding and pressure which considerably distort their working surfaces, and increase the hardness of the outside layers of the steel to over 500 Brinell. Typical examples of service of this sort are the breaking plates of rock crushers of many types; frogs, crossings, and switches in steam and electric-railway service; lining plates of ball and rod mills; steam-shovel dipper teeth and lips; orange peel and clam shell lips; ladder dredge buckets and tumblers for gold, platinum, tin, and gravel dredges; crane wheels; gears, pinions, racks, and sheaves of many types; and a great many similar machine parts. Though not absolutely proved, it appears probable that the ability of manganese steel to outwear other metals from 6 to 1 to as much as 20 to 1 in services of those kinds is due largely to the hardness imparted to it by the cold working to which it is subjected.

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[1] See John Howe Hall, "Studies of Hadfield's Manganese Steel with the High Power Microscope," H. M. Howe Memorial Lecture, *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Iron and Steel Division, p. 382 (1929); also V. N. Krivobok, "Study on the Constitution of High Manganese Steel," *Transactions*, Am. Soc. Steel Treating, Vol. XV, No. 6, p. 893 (1929).

[2] R. A. Hadfield and B. Hopkinson, "The Magnetic and Mechanical Properties of Manganese Steel," *Journal*, Iron and Steel Inst., Vol. 1, p. 106 (1914).

It is an undoubted fact that in services of the nature indicated the castings are hardened by the cold work, for a debth of about $\frac{1}{4}$ in., to over 500 Brinell. It appears probable that this intensely hard skin resists penetration and abrasion, and it does not tend to spall off because it shades gradually off into the strong, tough steel behind. Moreover, as the surface gradually wears away, the new metal exposed is at once hardened, so that throughout its life the piece is protected from rapid wear by a constantly renewed, wear-resisting skin. This line of reasoning is somewhat weakened by the fact that in most of the wearing tests so far devised,[1] little if any difference in resistance to pure abrasion can be detected between the work-hardened and un-work-hardened portions of a piece of manganese steel. The theory, however, is given strong confirmation by the fact that in almost every class of service in which manganese steel is a practical success, the wear is associated with heavy pressure and pounding which severely cold-works and hardens the surface of the castings; and by the further fact that, when exposed to pure abrasion without cold work, manganese steel does not surface-harden, and sometimes resists the wear no longer than hard metals like chilled iron, which it far excels in its own proper field.

In some types of services, the success or failure of a manganese steel part depends upon the class of material it is called upon to handle. The shifting of a shovel or dredge from a location where it is digging blasted rock or coarse gravel, to one where gritty loam or fine sand is to be moved, often results in an enormous increase in the wear of the manganese castings, because the impacts of the rock or heavy gravel harden them and increase their resistance to wear in a manner that is not possible when the material is subjected to pure abrasion of the loam or sand.

DISTORTION

A natural result of the distortion of the surface layers of manganese steel castings in service is that, in certain cases in which the cold working effect is severe and the purely abrasive condition less marked, there is spreading of the working face, warpage of castings, and, in extreme cases, even actual growth of dimensions throughout the thickness of the part at right angles to the force applied. Numerous instances can be cited in which manganese steel castings have broken or sheared off bolts and plates intended to hold them in place, buckled until they tore loose from their fastenings, and in other ways given trouble. Generally, of course, this flowing or peaning is confined to the surface of the castings, and is marked only in the initial stages of service. In these cases the slight change of shape is taken care of by casting the part a little thicker than desired, and either prepeaning with hammers or allowing the peaning to take place in service. In the less frequent cases where the flow is more extensive, it is compensated for by leaving spaces in the wearing surface of the casting and between adjacent castings, so that they may spread into the spaces for which they are intended without buckling or jamming against contiguous parts.

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[1] John Howe Hall, "Wearing Tests of Twelve-per-cent Manganese Steel," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 326 (1928).

MACHINING

Largely as a result of this hardening under severe cold work, manganese steel castings are commercially unmachineable. The best high-speed steels and some of the more recently perfected tools will cut the steel after a fashion, and castings have been turned and threaded in a lathe, drilled and planed, etc., but never at a cost to compare favorably with that of doing the same work by grinding with modern machine tools. Some of the more widely advertised tool steels, when put to actual test, have machined manganese castings, but while a demonstrator was machining one piece, a man in the same shop, working with a modern grinding machine, finished six.

It is greatly to be hoped that metals and tools will be developed that will economically machine manganese steel, since the cost of production of parts requiring accurate dimensions may thereby be greatly reduced.

RESISTANCE TO REPEATED OVERSTRESS

The fatigue limit of cast manganese steel, as shown earlier, is comparatively low, some 39,000 lb. per sq. in. As its limit of proportionality only slightly exceeds the fatigue limit, and as stressing beyond the elastic limit naturally results in cold work and hardening, it therefore follows that manganese steel will not very long resist repeated stresses that exceed its rather low limit of proportionality. Such stresses result in rapid hardening of the parts subjected to the maximum stress, with consequent loss of toughness; a crack soon starts in the hardened layers, and such a crack, once started, spreads rapidly. For this reason it is essential that the dimensions of manganese-steel castings that are to endure repeated heavy stresses should be such as to keep the unit stress within safe limits.

WELDING

Until quite recently attempts to repair worn or cracked manganese-steel castings by autogenous welding were so often unsuccessful that the process could hardly be called practical. The author, in discussion this question at the A.S.T.M. Welding Symposium in 1931,[1] showed that the failure of welds in manganese steel is due generally to the damage done to the steel close to the weld by the heat of the arc or flame. Part of this damage is due to the brittleness produced by heating the steel to a dark red heat, as already described, and is remediable by complete re-heat treatment of the casting. The steel is also weakened, however, by the partial fusing of a layer of metal which is brought almost, but not quite, to its melting point, and is consequently subjected to true "burning." This damages the manganese steel, regardless of whether or not the weld is protected by flux coatings, inert gas, or the like, and the damage is only in part remediable by re-heat treatment. For this reason welds in manganese steel, even when the castings have been re-heat treated, have until recently not often been successful. The welded part far too often broke away in service, the failure generally taking place in the casting close to the weld rather than in the weld metal. As a result attempted repairs of worn places usually resulted in the weld "coming out" in a comparatively short time, and bringing some of the underlying casting along with it, so that the case was worse than before the weld was made.

This condition was found to be true even when the composition of the metal deposited in welding was identical with that of the casting being repaired. The leading makers of manganese steel have recently discovered that by incorporating from 3 to 5 per cent of nickel in manganese steel welding rods, and sometimes by the use also of rods of a low carbon content, the embrittling effect of the welding heat can be largely offset by the impregnation of the contact zone with nickel, and the dilution of its carbon content when the low-carbon rod is used. Electric arc welds made with these rods rarely require re-heat treatment, and successful jobs can be done with the torch also, though gas welds almost always require complete re-heat treatment, because the underlying manganese steel is affected to a much greater extent by the heat of the flame than by the arc. To heat only the part of the casting containing the weld and quench that part in water, of course, is usually of no avail, because at the zones where the casting is brought only to dark red, the steel is made brittle, even after quenching. To keep the casting cool by laying it in water during the welding, only to a limited extent prevents the damage due to heating the manganese steel, for obviously there must be a zone around any weld where the metal was almost, but not quite, fused, and a zone where it was just red hot. If the casting be cooled with water, these zones will be closer to the weld; if it is allowed to heat up, they will be further from it. But to prevent their occurrence is impossible, and their presence weakens the steel considerably.

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[1] John Howe Hall, Discussion of paper by A. M. Candy on, "Modern Applications of Arc Welding," Symposium on Welding, Pittsburgh Regional Meeting, Am. Soc. Testing Mats. (1931). (Separate volume.)

With the newly developed nickel manganese steel welding rods, worn manganese steel castings are being successfully repaired and returned to service in a wide variety of applications, such as rock crushing, material handling, dredging, etc.; electric-railway frogs, crossings, and switches are built up at the worn parts, and even broken castings are reclaimed; and the steam railroads are rapidly extending their operations in salvaging worn-out manganese steel "special work." In main-line service, where a failure may mean serious loss of life, it is the belief of the author and his associates that railroad engineers should feel their way in this matter, and test out any very extensive welding jobs in yard service and other points where the consequences of failure would not be disastrous, and where the train speeds are low. In particular, makers of manganese steel trackwork are trying to encourage the building up of worn parts at short intervals, rather than at long intervals, so that the total amount of metal deposited will be slight and the damage to the underlying steel will be less extensive. With proper control of welding conditions, manganese steel casting makers are looking forward to the time, believed to be near at hand, when autogenous welding will be regularly used to extend the life of manganese steel parts, with the result that the cost of manganese steel, per unit of service rendered, will be reduced, so that its use will become advisable in many places where it was formerly considered too costly to pay for itself.

DISCUSSION

MR. C. S. KOCH.[1]—I should like to ask Mr. Hall if austenitic manganese steel castings can be welded to carbon steel castings.

MR. J. H. HALL.[2]—We have now worked out a technique by which we can weld manganese steel to straight carbon steel of practically any analysis. We do that by the use of nickel-manganese steel welding rods, which stick to the manganese steel, and another welding rod which sticks to the carbon steel, and as fortunately the two stick to each other we get a strong weld. With this method of welding we have been able to perfect a new design of street railway track work in which manganese steel castings are welded to rail steel to make a solid unit. By actual test this design is half again as strong as the old fashioned "keyed center" parts formerly furnished for similar installations.

A MEMBER.—I should like to ask if you have any difficulties from shock or jars?

MR. HALL.—In welded track work, for instance? No. We have in service electric railway switch tongues which have been broken completely in two and welded together. The first one I know of went in service December 1, 1929, under street railway and heavy interurban cars, and it is in the track now, and we have quite a few installations of steam railway track work which have been welded where worn. We do think, however, that the steam railroads should "feel their way along" a bit in welding, and particularly that they should weld at frequent intervals rather than allow a large amount of wear to take place before welding, on account of the harmful influence of heat on the underlying manganese steel.

MR. G. E. DOAN.[3]—I should like to ask Mr. Hall whether the heat from fusion welding does not destroy the austenitic structure obtained by quenching from 1900° F. (1035° C.), and if not whether this deterioration is prevented by welding a short distance and then cooling the weld with water, or whether that is not necessary.

MR. HALL.—The arc and particularly the gas torch of course do produce brittleness in the underlying manganese steel by producing what we call a re-heated structure, because the carbides which have been brought into solution by the quench are liberated at a dark red heat. Surrounding any weld in Hadfield's manganese steel is a more or less weak and brittle zone, and that zone is two fold. There is an outer layer which has been brought to a dark red heat and which is brittle from the liberation of carbides; that zone will be brittle whether the weld has been quenched or not. In addition, at the weld is a zone which has been almost, but not quite, melted, which has been brought above the solidus and below the liquidus, and that zone has lost its toughness permanently. Neither quenching the weld, nor re-heat treating the whole casting will fully restore the strength of this truly "burned" layer. It was for that reason that, as long as welding was done with unmodified manganese steel rods welds in manganese steel were so unreliable. The new welding rods contain a high percentage of nickel in addition to the manganese, and usually a much lower carbon content than that of standard manganese steel. By using a low-carbon rod, we greatly reduce the carbide liberation at a red heat, and by nickel impregnation, we largely prevent the loss of strength and toughness due to semi-fusion close to the weld. It is shown by any number of laboratory tests and by an increasing number of service tests, that welds made in manganese steel with nickel manganese rods are very much stronger than welds made with straight manganese steel rods. Repair jobs are being successfully made today with the new rods that could not be done at all with plain manganese steel rods.

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[1] President, Fort Pitt Steel Castings Co., McKeesport, Pa.

[2] Technical Assistant to President, Taylor-Wharton Iron and Steel Co., High Bridge, N. J.

[3] Assistant Professor, Department of Metallurgical Engineering, Lehigh University, Bethlehem, Pa.

PROBLEMS AND PRACTICES IN THE HEAT TREATMENT OF STEEL CASTINGS

By A. W. Lorenz[1]

The development, in recent years, of heat treating practices designed to meet special requirements, has constituted a distinct advance in the manufacture of cast steel products. Whereas the heat treatment of steel castings once implied nothing more than a simple annealing, such castings are now being supplied in the full-annealed, the normalized, and the liquid-quenched condition. Suitable drawing or tempering, especially after oil or water quenching, provides modifications of properties to meet a wide range of requirements.

Definitions of terms relating to heat treatment operations have been prepared by a joint committee representing the American Society for Steel Treating, the American Society for Testing Materials and the Society of Automotive Engineers. These definitions, as approved by these several organizations, and including some few minor revisions recently recommended by the joint committee, are given below:

Full Annealing.—Heating iron-base alloys above the critical temperature range, holding above that range for a proper period of time, followed by slow cooling through the range.

Note.—The annealing temperature is generally about 100° F. (55° C.) above the upper limit of the critical temperature range, and the time of holding is usually not less than one hour for each inch of section of the heaviest objects being treated. The objects being treated are ordinarily allowed to cool slowly in the furnace. They man, however, be removed from the furnace and cooled in some medium which will prolong the time of cooling as compared to unrestricted cooling in the air.

Normalizing.—Heating iron-base alloys to approximately 100° F. (55° C.) above the critical temperature range followed by cooling to below that range in still air at ordinary temperature.

Note.—Normalizing is rarely practiced with hypereutectoid steels because of the coarsening of the grain and the tendency to crystallize cementite at grain boundaries or in needles. However, it may sometimes be necessary to normalize these steels by heating them above the Ac_{cm} line of the iron carbon diagram.

Spheroidizing.—Prolonged heating of iron-base alloys at a temperature in the neighborhood of, but generally slightly below, the critical temperature range, usually followed by relatively slow cooling.

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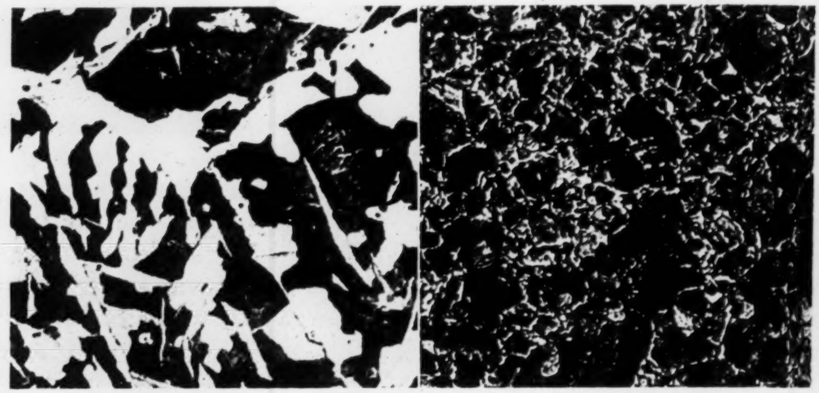
[1] Metallurgist, Bucyrus-Erie Co., South Milwaukee, Wis.

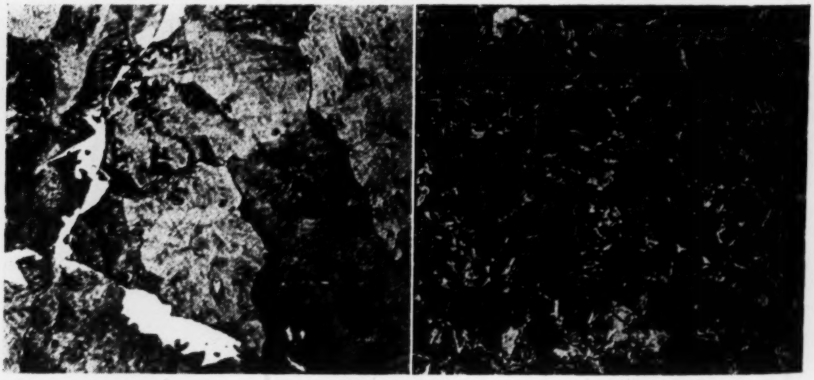
NOTE 1.—In the case of small objects of high-carbon steels, the spheroidizing result is achieved more rapidly by prolonged heating to temperatures alternately within and slightly below the critical temperature range.

NOTE 2.—The object of this heat treatment is to produce a globular condition of the carbide.



(a) As cast. (b) Water quenched.

FIG. 1.—Low-Carbon Steel. Etched in 2 per cent Nital (× 100).



(a) As cast. (b) Water quenched.

FIG. 2.—Intermediate Manganese Steel. Etched in 2 per cent Nital (× 100).

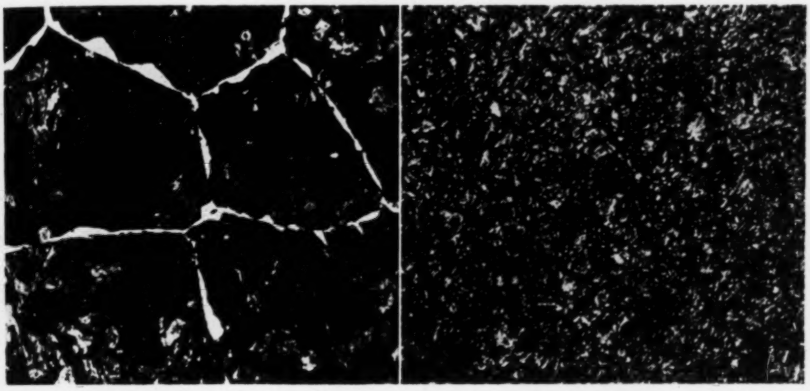
Tempering (also termed Drawing).—Reheating iron-base alloys, after hardening, to some temperature below the critical temperature range followed by any desired rate of cooling.

NOTE 1.—Although the terms "tempering" and "drawing" are practically synonymous as used in commercial practice, the term "tempering" is preferred.

NOTE 2.—Tempering, meaning the operation of hardening followed by reheating, is a usage which is illogical and confusing in the present state of the art of heat treating and should be discouraged.

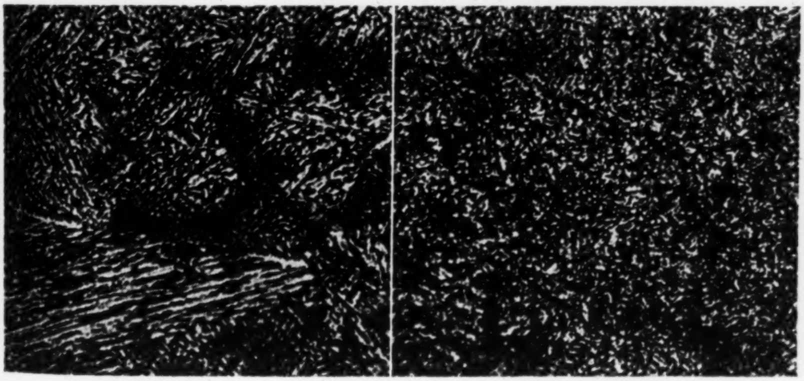
The results to be obtained by these various treatments may be briefly summarized as follows:

Full Annealing.—This treatment effects removal of strain, improves machineability and ductility. In some cases it may be the only practical method of treatment, due to size of casting, maintenance of dimensions, or other limitations.



(*a*) As cast. (*b*) Water quenched.

Fig. 3.—Nickel-Chromium Steel. Etched in 2 per cent Nital (× 100).



(*a*) As cast. (*b*) Water quenched.

Fig. 4.—Nickel-Chromium-Molybdenum Steel. Etched in 2 per cent Nital (× 100).

Normalizing.—This largely increases the yield point and tensile strength as compared with full annealing, particularly on alloy steels. In high-carbon and alloy castings, strains and brittleness will usually be induced, unless followed by a tempering or drawing treatment. When these castings are both normalized and tempered, they will possess better ductility, higher yield point and strength, and considerably better impact and fatigue properties than castings in the full-annealed condition.

Liquid Quenching.—This treatment confers maximum strength and hardness. It should almost always be followed by tempering to remove quenching strains and brittleness, and to secure suitable modification of properties. When followed by such a treatment, most carbon- and alloy-steel castings will develop the maximum combination of strength and ductility.

Tempering or Drawing.—This increases ductility, removes strains, and softens the material, improving machineability. It is properly applied only after one of the previously mentioned treatments. When used after liquid quenching, this treatment provides a means of adjusting the hardness and other working properties within a wide range to suit individual requirements.

It will be observed from the above that the objects and practices in the heat treatment of steel castings are essentially the same as for forgings. There is, however, the difference that, with steel castings, difficulties exist in breaking up the cast structure, with its large grain size and inherent segregation. In order to bring about proper refinement, it is usually necessary that at least one heating shall be conducted at a temperature considerably above the upper critical point, and often for a prolonged period of time. If this heating is to be followed by further treatments, the latter may closely approximate the practice for forgings of similar type.

The extreme coarseness of the original structure, and the grain refinement possible with careful treatment, are illustrated in the accompanying photomicrographs (Figs. 1 to 4). These represent, respectively, the structures of plain carbon, intermediate manganese, nickel-chromium, and nickel-chromium-molybdenum steels.

The following sections will consider in detail some of the more important factors in the treatment of steel castings, especially with regard to full-annealing and normalizing practice. Inasmuch as the same general practices apply to carbon and alloy castings, both kinds of steel will be discussed collectively.

FULL-ANNEALING AND NORMALIZING PRACTICE

The A.S.T.M. Recommended Practice for the Heat Treatment of Carbon-Steel Castings (A 36 – 24) advocates full-annealing and normalizing temperatures as follows:

CARBON, PER CENT	TEMPERATURE
Up to 0.40, inclusive	1650° F. (900° C.)
Over 0.40 to 0.60, inclusive	1560° F. (850° C.)
Over 0.60	1525° F. (830° C.)

The A.S.S.T. recommended temperatures for single full-annealing or normalizing of carbon-steel castings[1] are in substantial agreement with the above, as follows:

CARBON, PER CENT	TEMPERATURE
0.15 to 0.40	1600 to 1700° F. (870 to 925° C.)
0.40 to 0.60	1550 to 1600° F. (840 to 870° C.)

Others [2, 3] advocate temperatures approximating 1650° F. for plain carbon castings, while for alloy steels of various types, temperatures of 1600 to 1800° F. (870 to 980° C.) have been recommended.[4] The author questions the need of making any distinctions between steels ranging between 0.15 to 0.60 per cent carbon, since other factors have such a determining influence as to render carbon content of minor importance. Of much greater importance are the factors of holding time and mass. H. A. Neel[3] was one of the first to show that holding time and temperature are closely inter-related, a fact which has been generally accepted. Mass has a decided bearing on both holding time and temperature, since the difficulty of refining the cast structure increases with the size of the object.

This is due not only to the difficulties attendant upon treating a large body, but also and more particularly to the initial rate of cooling during and after solidification, which has a marked influence on the structure of the metal. Sauveur has suggested[5] that some types of structure may be more difficult to refine than others, and hence require different treatment. He raises the question, "Will a network structure respond to the annealing treatment more readily than the Widmanstatten structure, and should it therefore be promoted in our castings? It is not likely that both behave in a similar manner; one must be preferable and should be induced. . . . This opens up an important field for investigation."

V. N. Krivibok[6] has pursued this matter further, and has presented some interesting data showing that either the Widmanstatten or the network structure may be induced at will by regulating the rate of cooling through the granulation zone and the zone of secondary crystallization. Slow cooling induces the Widmanstatten structure; rapid cooling promotes the network structure.

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[1] "Recommended Practice for the Heat Treatment of Carbon Steel Castings," *National Metals Handbook*, Am. Soc. Steel Treating, 1930 edition, p. 138.

[2] B. Egeberg, "The Heat Treatment of Cast Steel for Hydroelectric Power Machinery," *Transactions*, Am. Soc. Steel Treating, Vol. III, p. 422 (1923).

[3] H. A. Neel, "Heat Treatment of Steel Castings," *Transactions*, Am. Foundrymen's Assn., Vol. XXXI, p. 203 (1923).

[4] "Recommended Practice for the Heat Treatment of Alloy Steel Castings," *National Metals Handbook*, Am. Soc. Steel Treating, 1930 edition, p. 142.

[5] Albert Sauveur, "The Metallography and Heat Treatment of Iron and Steel," third edition, p. 160.

[6] V. N. Krivibok, "Secondary Crystallization in Iron-Carbon Alloys," *Transactions*, Am. Soc. Steel Treating, Vol. VII, p. 457 (1925).

While these findings are interesting in explaining the mechanism by which certain types of cast structure are formed, it is difficult for the foundryman always to make use of this knowledge for the purpose of simplifying heat treatment. It is evident that castings of large mass cannot be rapidly cooled, and that the rate of cooling after casting is not always a matter of choice. Consideration must therefore be given to the fact that different types of structure will be encountered, and that it will be necessary to modify the treatment accordingly.

Considering all the above factors, it may well be questioned why carbon content should have major significance. General experience indicates that temperatures around 1600 to 1650° F. (870 to 900° C.) are quite satisfactory for small and medium-sized castings in a wide variety of compositions of carbon and alloy steels, when only a single treatment is required. Where it is desirable to provide a double treatment above the critical range, the preceding statement must be qualified, because the second treatment should be governed closely by the composition of the metal.

In the field of heavy castings, some difference of opinion exists, and it appears quite possible that no set temperature or method of treatment will cover all conditions. There is a noticeable trend on the part of some manufacturers and users of heavy castings to modify the standard procedure. Not much published information is available, but inquiry among a number of the larger foundries in this country indicates that for such castings, temperatures of 1700 to 1900° F. (925 to 1035° C.) are occasionally employed, followed by a second heating to just above the upper critical point. On the other hand, a large foundry group with unquestioned research facilities advises that even where double treatments above the critical point are employed, they never exceed 1650° F. (900° C.).

MacPherran and Harper,[1] also Harper and Stein,[2] have published results obtained on heavy castings by means of double and triple treatments. Temperatures ranging from 1600 to 1750° F. (870 to 955° C.) were employed on the first heating. This was followed usually by a second heating slightly above the upper critical point to refine the grain, and finally by a spheroidizing treatment at approximately 1290° F. (697° C.), which is the distinguishing feature of the process. The test specimens were invariably taken from the body of the casting, and the results shown are excellent.

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[1] R. S. MacPherran and J. F. Harper, "Spheroidized Cementite in Hypoeutectoid Steel," *Transactions*, Am. Soc. Steel Treating, Vol. IV, p. 341 (1924).

[2] J. F. Harper and H. J. Stein, "The Microscope as a Controlling Instrument in Annealing Steel Castings," *Transactions*, Am. Foundrymen's Assn., Vol. XXXII, Part I, p. 679 (1924).

W. J. Merten[1] has published the results of an investigation involving treatments as high as 2012° F. (1100° C.). The high-temperature treatment was followed by a second heating at 1600° F. (870° C.) and a third at 1275° F. (690° C.). While presumably the data show the advantages of high-temperature treatments, the introduction of a final tempering or drawing operation may have had no small influence on the observed increase in ductility.

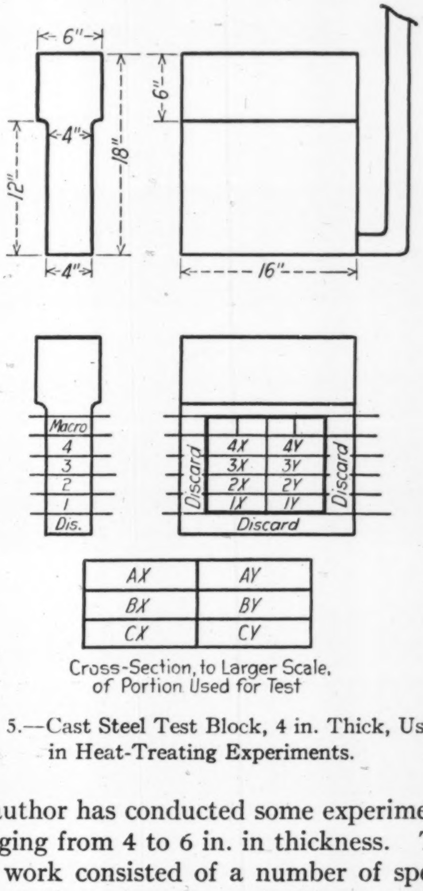
6"
4"
12"
18"
6"
4"
16"
Macro
4
3
2
1
Dis.
4X
4Y
3X
3Y
2X
2Y
1X
1Y
Discard
Discard
Discard
AX
AY
BX
BY
CX
CY
Cross-Section, to Larger Scale, of Portion Used for Test

FIG. 5.—Cast Steel Test Block, 4 in. Thick, Used in Heat-Treating Experiments.

The present author has conducted some experiments on medium-sized sections, ranging from 4 to 6 in. in thickness. The material for this experimental work consisted of a number of special test blocks having the form and dimensions shown in Figs. 5 and 6. The heavy section at the top fills the function of a feeder to assure soundness in the material under test. The lower sections of these castings were sliced with a cold-saw and the individual slices were subjected to various treatments.

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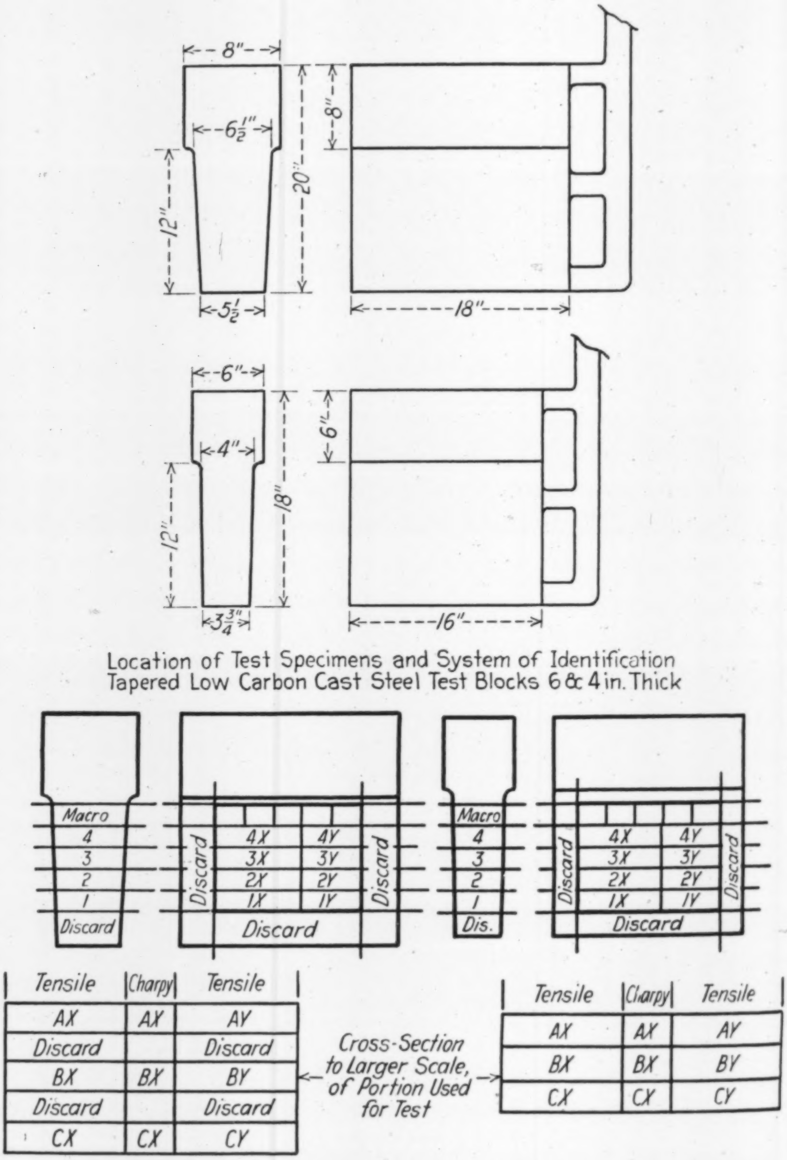
[1] W. J. Merten, "High Temperature Treatment of Castings and Forgings," *Transactions*, Am. Soc. Steel Treating., Vol. XIII, p. 1 (1928).


8"
6½"
20"
8"
12"
5½"
18"
6"
4"
18"
6"
12"
3¾"
16"
Macro
4
3
2
1
Discard
4X
4Y
3X
3Y
2X
2Y
1X
1Y
Discard
Discard
Discard
Macro
4
3
2
1
Dis.
4X
4Y
3X
3Y
2X
2Y
1X
1Y
Discard
Discard
Discard
Cross-Section to Larger Scale, of Portion Used for Test

Location of Test Specimens and System of Identification
Tapered Low Carbon Cast Steel Test Blocks 6 & 4 in. Thick

Tensile	Charpy	Tensile
AX	AX	AY
Discard		Discard
BX	BX	BY
Discard		Discard
CX	CX	CY

Tensile	Charpy	Tensile
AX	AX	AY
BX	BX	BY
CX	CX	CY

FIG. 6.—Cast Steel Test Blocks Used in Later Heat-Treating Experiments.

TABLE I.—PHYSICAL PROPERTIES WITH VARIOUS TREATMENTS FROM CAST STEEL TEST BLOCK 4 IN. THICK, SHOWN IN FIG. 5.

CHEMICAL COMPOSITION: Carbon 0.28 per cent, manganese 0.87 per cent, silicon 0.36 per cent, sulfur 0.046 per cent, phosphorus 0.021 per cent.

SLAB	POSITION	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
1	A	81 250	48 300	7.0	6.9
	B	70 050	44 750	3.0	3.9
	C	79 750	47 700	4.0	7.3
2	A	79 750	54 300	10.0	11.8
	B	71 500	51 100	6.0	8.5
	C	79 050	53 200	9.5	11.8
3	A	77 800	51 050	16.0	18.4
	B	73 100	47 600	12.5	15.9
	C	77 900	49 700	18.5	23.4
4	A	85 400	63 800	11.0	17.0
	B	80 950	58 650	12.0	15.7
	C	86 200	61 950	14.5	21.6

TABLE II.—HEAT TREATMENT OF SLABS SHOWN IN FIG. 6.

SPECIMEN NUMBERS	TREATMENT NUMBER	TREATMENT
		4-IN. BLOCK
1X and 4Y	1	Heated to 1650° F. (900° C.), held 2½ hours, air-cooled. Drawn at 1100° F. (595° C.) for 5 hours.
4X and 1Y	2	Heated to 1650° F. (899° C.), held 8 hours, air-cooled. Drawn at 1100° F. (595° C.) for 5 hours.
2X and 3Y	3	Heated to 1850° F. (1010° C.), held 12 hours, air-cooled. Heated to 1600° F. (870° C.), held 2 hours, air-cooled. Drawn at 1100° F. (595° C.) for 5 hours.
3X and 2Y	4	Heated to 1850° F. (1010° C.), held 12 hours, air-cooled. Heated to 1600° F. (870° C.), held 6 hours, air-cooled.
		6-IN. BLOCK
1X and 4Y	1	Heated to 1650° F. (900° C.), held 2½ hours, air-cooled. Drawn at 1100° F. (595° C.) for 5 hours.
4X and 1Y	2	Heated to 1650° F. (900° C.), held 12 hours, air-cooled. Drawn at 1100° F. (595° C.) for 5 hours.
2X and 3Y	3	Heated to 1825° F. (995° C.), held 12 hours, air-cooled. Heated to 1600° F. (870° C.), held 2 hours, air-cooled. Drawn at 1100° F. (595° C.) for 5 hours.
3X and 2Y	4	Heated to 1825° F. (995° C.), held 12 hours, air-cooled. Drawn at 1100° F. (595° C.) for 5 hours

TABLE III.—PHYSICAL TESTS FROM BLOCKS SHOWN IN FIG. 6.

SPECIMEN	TREATMENT	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT	CHARPY IMPACT, FT-LB.
		4-IN. BLOCK				
1-AX	1	74 650	47 700	31.5	52.0	23.28
4-AY	1	75 450	46 250	25.5	32.1	
4-AX	2	77 050	48 750	27.0	37.6	17.73
1-AY[a]	2	74 800	47 000	29.5	26.4[a]	
2-AX	3	75 600	46 600	32.0	47.2	22.72
3-AY	3	74 200	46 700	27.0	42.7	
3-AX	4	75 100	47 800	28.0	36.6	19.05
2-AY	4	74 700	49 000	30.5	47.2	
1-BX	1	72 250	44 950	30.5	46.9	22.58
4-BY	1	72 050	45 300	28.5	41.0	
4-BX	2	72 550	46 250	24.5	33.1	24.14
1-BY	2	72 650	44 200	31.0	46.0	
2-BX	3	72 650	44 900	31.0	44.0	22.16
3-BY	3	72 000	47 000	30.0	40.0	
3-BX	4	72 500	47 600	27.5	34.7	25.71
2-BY	4	72 250	45 100	32.0	44.0	
1-CX	1	74 300	46 350	28.5	49.2	22.02
4-CY	1	75 250	47 250	25.0	39.7	
4-CX	2	75 500	48 500	25.5	35.7	19.71
1-CY	2	75 000	46 550	28.0	42.2	
2-CX	3	75 700	49 350	26.5	41.0	22.16
3-CY	3	74 200	48 250	27.5	44.0	
3-CX	4	74 700	45 900	30.0	42.2	23.28
2-CY	4	74 900	48 150	29.5	45.1	
		6-IN. BLOCK				
1-AX	1	75 750	45 650	31.5	46.9	18.92
4-AY	1	74 300	45 200	27.5	42.8	
4-AX	2	75 450	47 950	23.5	36.6	19.18
1-AY	2	75 000	48 950	26.5	38.8	
2-AX	3	74 300	46 200	28.5	44.0	20.38
3-AY	3	74 600	50 050	29.5	43.4	
3-AX	4	74 400	50 450	30.0	48.9	19.45
2-AY	4	74 100	47 400	31.5	41.9	
1-BX	1	71 350	45 075	28.5	48.3	24.71
4-BY	1	71 900	45 900	23.5	38.2	
4-BX	2	71 900	43 450	27.0	36.3	27.76
1-BY	2	71 700	43 800	29.5	46.3	
2-BX	3	71 100	46 250	29.0	42.8	24.56
3-BY	3	71 550	43 800	31.5	48.6	
3-BX	4	71 350	46 750	30.0	41.9	30.77
2-BY	4	71 300	46 300	31.0	45.4	
1-CX	1	75 550	48 350	27.5	43.1	20.24
4-CY	1	75 150	49 100	25.0	43.4	
4-CX[a]	2	76 650	47 350	24.0	22.7[a]	20.24
1-CY	2	74 950	46 250	23.5	31.5	
2-CX	3	74 700	49 050	30.0	44.9	24.85
3-CY	3	74 400	45 400	25.0	32.1	
3-CX	4	74 100	46 850	26.2	36.9	22.02
2-CY	4	72 900	49 350	29.5	46.0	

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[a] Test specimen machined incorrectly to 0.485 in.

The first block to be cast for these experiments was 4 in. thick, and the sides were without taper, as shown in Fig. 5. Four slices were cut from the lower section and treated as follows:

Slice No. 1 tested as cast.

Slice No. 2 heated to 1675° F. (910° C.), held three hours, given a modified air-cool requiring one hour to drop to 900° F. (480° C.) followed by a draw heat at 1250° F. (675° C.).

Slice No. 3 heated at 1900 to 2000° F. (1035 to 1095° C.) for 17 hours, cooled in one and one-half hours to 900° F. (480° C.), reheated at 1675° F. for three hours, and drawn at 1250° F. (675° C.).

Slice No. 4 received the full treatment given to No. 3, followed by a water-quench from 1600° F. (870° C.) and a draw at 1250° F. (675° C.).

Results are shown in Table I. Ductility is decidedly poor throughout the series, but is much better for slice No. 3 treated at 1900 to 2000° F. (1035 to 1095° C.) than for slice No. 2 treated at 1675° F. (910° C.).

Because of the generally poor results shown in this test, two new blocks were cast, having an average thickness of 4 and 6 in., respectively, and having tapered sides (Fig. 6). The method of gating was also changed. The manner of slicing and marking is indicated. The analysis of these blocks was: carbon, 0.28 per cent; manganese, 0.67 per cent; silicon, 0.36 per cent; sulfur, 0.016 per cent; phosphorus, 0.008 per cent.

Treatments given the various slices are shown in Table II. Physical results are shown in Table III. The very interesting feature of these results is that all of the tests are good, regardless of location and regardless of treatment. Results obtained at 1650° F. (900° C.) are almost identical with those obtained at 1800° F. (980° C.).

Some time previous to this test, a 4-in. tapered block was cast of nickel-chromium steel. This block was gated at the bottom only. The system of identification of the various test specimens was similar to that used in the experiments just described. In this test, one-half of each slice was heated at 2000° F. (1095° C.), for eight hours, cooled slowly to 1700° F. (925° C.), then removed from the furnace, and cooled in air. This was followed by heating to 1550° F. (840° C.), holding two hours, water-quenching, and tempering for one and one-half hours at 1200° F. (650° C.). This end is designated by the suffix *X*. The opposite half (end *Y*) was treated in exactly the same manner, except that it did not receive the preliminary treatment at

2000° F. (1095° C.). Slices Nos. 1 and 4 were used for tension tests, and slices Nos. 3 and 6 for Charpy tests. Results are given in Table IV. In every instance, the triple treatment has resulted in better ductility, but it may be questioned whether the improvement is sufficient to justify the added expense.

Between all the above series of tests a lack of agreement is shown, and it becomes evident that design and other factors have such a decided effect that no definite conclusions can be drawn as to the effect of a given treatment. After considering all available data, the evidence is not conclusive enough to demonstrate without considerable qualification, the advantages of extremely high-temperature treatments. Nevertheless, there is enough promise in such treatments to warrant further investigation. It is possible that temperatures above 2000° F. (1095° C.) may exert an influence in directions which have received little attention. Smithells,[1] for instance, advances the thought that sub-microscopic inclusions may be moved bodily at

TABLE IV.—PHYSICAL RESULTS FROM NICKEL-CHROMIUM STEEL TEST BLOCK 4 IN. THICK.

SPECIMEN	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT	CHARPY IMPACT, FT-LB.
1-AX	116 750	95 350	20.0	52.0	....
1-BX	108 500	89 500	14.0	25.1	....
1-CX	120 750	100 950	19.5	53.9	....
1-AY	120 100	101 150	20.0	46.0	....
1-BY	114 700	96 950	9.0	20.6	....
1-CY	120 700	100 800	22.0	48.6	....
3-AX	......	......	....	....	24.6
3-BX	......	......	....	....	23.6
3-CX	......	......	....	....	26.8
3-AY	......	......	....	....	21.3
3-BY	......	......	....	....	17.3
3-CY	......	......	....	....	22.7
4-AX	119 500	99 850	19.5	52.9	....
4-BX	111 750	90 250	12.5	23.4	....
4-CX	121 250	101 550	19.0	52.8	....
4-AY	......	flawed bar	....	....	....
4-BY	115 500	95 000	10.0	18.4	....
4-CY	120 800	100 400	19.0	45.4	....
6-AX	......	......	....	....	24.6
6-BX	......	......	....	....	28.1
6-CX	......	......	....	....	25.9
6-AY	......	......	....	....	23.9
6-BY	......	......	....	....	22.4
6-CY	......	......	....	....	22.2

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[1] C. J. Smithells, "Impurities in Metals," second edition, p. 87.

temperatures approaching the melting point of a metal, while Ritchie, in describing the manufacture of special centrifugally-cast guns at Watertown Arsenal[1] makes the significant statement that material resembling oxide streaks was apparently dispersed at temperatures around 2000° F., but not at lower temperatures.

RATE OF COOLING

Up to the present time, standard recommended practices of the American Society for Testing Materials have definitely recognized two types of cooling practice: namely, furnace-cooling or full-annealing, and air-cooling or normalizing. The higher properties obtainable by air-cooling are so marked, that in the field of small and medium-sized castings, this practice has received widespread adoption. With large castings, there may be no alternative but to furnace-cool, so that the rate of cooling may not always be a matter of choice.

In line with the tendency toward rapid cooling, there is an increasing trend toward liquid quenching. The fear that such a practice is dangerous is gradually losing ground. In the author's experience, many thousands of tons of steel castings have been given water-quenching treatments, with a loss of only a few hundredths of one per cent, and these cases could invariably be traced to prior causes. Mention of this is made for the reason that two specifications for steel castings prohibit the use of liquid quenching treatments.[2]

As regards the two factors, the full-annealing or normalizing temperature (within the limits of our previous discussion), and the rate of cooling, the latter seems to have by far the greater effect on physical properties.

HOLDING TIME

The time of holding at heat is variously recommended to be from one-half to one hour, or longer, per inch of cross-section. The usual practice is about one hour per inch of cross-section of the heaviest casting in the charge, except for large castings, which are ordinarily held much longer. In some cases the time for large castings may exceed two hours per inch of thickness.

Clarke has cited several interesting examples bearing on the matter of strain relief in steel castings, as affected by holding time. By means of the Laue pinhole method, it was found[3] that twenty hours annealing at 1650° F. (900° C.) was required in one instance to remove all traces of strain in a casting only ½ in. thick. This was probably an unusual case, as Clarke reports some later investigations[1] conducted for a large manufacturer of steel castings, in which it was found that even in larger castings a satisfactory structure could be obtained in as little as one-half hour.

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[1] S. B. Ritchie, "Steel Made Without Manganese," *Metal Progress*, September, 1931, pp. 39, 118.

[2] Standard Specifications for Steel Castings (A 27 – 24), and Standard Specifications for Carbon-Steel Castings for Valves, Flanges and Fittings for High-Temperature Service (A 95 – 29), 1930 Book of A.S.T.M. Standards, Part I, pp. 227 and 264, respectively.

[3] G. L. Clarke, "Applied X-rays," first edition, p. 232.

LIQUID QUENCHING

Liquid quenching of steel castings involves no unusual procedure. The quenching medium may be either oil or water. Water is more generally used. The temperature of the quenching water is maintained as a rule above 100° F. (38° C.), and most frequently at from 125 to 150° F. (50 to 65° C.). If the casting has had no previous treatment, it is the usual practice to quench from a heat approximating ordinary normalizing temperatures or slightly lower. Temperatures of 1550 to 1650° F. (840 to 900° C.) are commonly employed, depending on composition. If the castings have been previously normalized, the quenching may be conducted at temperatures about twenty-five to fifty degrees lower. Where critical detection apparatus is available, very satisfactory results have been obtained on small parts by quenching just as the temperature passes above the upper critical point. Where minimum distortion or maximum impact properties are desirable, it has been suggested to heat to just above the upper critical point on heating, Ac_3, and then to cool down to very slightly above the upper critical point on cooling, Ar_3, before proceeding to quench.

In the handling of castings after quenching, it is quite important that they be removed from the quenching bath while still warm, and it is a great advantage to transfer to the drawing furnace immediately.

While it is sometimes recommended that castings be full-annealed or normalized before quenching, inquiry reveals that a considerable tonnage of commercial castings receives no preliminary treatment. A number of foundries specializing in liquid-quenching treatments are apparently obtaining excellent results without recourse to a preceding full-anneal or normalization. It is probable that for the bulk of commercial work, normalizing involves an unnecessary expense. In some special instances, however, these same foundries have resorted to preliminary treatments. It is the author's experience that the double treatment results in somewhat finer and more uniform structure, with higher impact values, though not necessarily of an order to justify its use in general practice.

Normalizing or full-annealing is sometimes necessary prior to quenching, as a matter of processing, to facilitate machining, to reduce distortion, and to minimize danger of cracking where cold parts are introduced directly into a hot furnace for quenching. These considerations are of interest mainly to the producer.

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[1] G. L. Clarke, "X-ray Metallography in 1929," *Metals and Alloys*, November, 1929, p. 206.

TEMPERING OR DRAWING, AND SPHEROIDIZING TREATMENTS

The ductility of cast steel can be considerably improved by tempering or drawing, and spheroidizing treatments, ranging from 750 to 1400° F. (400 to 760° C.), a fact which has been known for some time, but not widely appreciated. Tempering treatments are necessary in practically all cases after liquid quenching, but the employment of similar treatments after normalizing, and sometimes even after full-annealing, has not received much attention outside the foundry. There, the practice of reheating within or slightly below the critical range is quite common in the case of alloy steels, and is growing in the treatment of plain carbon steels. It need only be pointed out that practically all published data on methods of treatment for heavy castings, or castings for special purposes, involve tempering or spheroidizing as the final step. The data may stress the details, such as temperature or cooling rate, of some prior step, but the significance of the final treatment should not be overlooked.

LIQUID QUENCHING OF LOW-CARBON STEEL CASTINGS

Previous reference has been made to liquid quenching. The chief application of liquid quenching up to the present time has been in the treatment of alloy castings. As a general statement, it may be said that liquid quenching of alloy-steel castings is capable of developing ultimate strength and yield point characteristics at least fifty per cent higher than those typical of the metal in the normalized condition, without appreciable loss of ductility. The heat treatment of alloy-steel castings is a large field within itself. It is not possible here to consider in detail the large variety of analyses which are now obtainable, but it may be stated briefly that with suitable liquid quenching and tempering treatments, the greater proportion will develop properties within the following range:

Tensile strength, lb. per sq. in	120 000 to 200 000
Yield point, lb. per sq. in	80 000 to 175 000
Elongation in 2 in., per cent	30 to 10
Reduction of area, per cent	60 to 25

While the liquid quenching and tempering of alloy-steel castings has received considerable attention, it is not so widely known, probably, that liquid-quenched low-carbon steel castings are being produced in considerable tonnages at the present time. In some cases they are being offered as the manufacturer's preference in substitution for full-annealed or normalized castings. Some typical results obtained by the author are shown in Table V.

The following table, reprinted from an article by H. A. Mitchell,[1] shows the average properties of a carbon-steel casting with various treatments, and the percentage improvement due to quenching treatments:

It is apparent from the above that water-quenched low-carbon steel castings offer an economical substitute for normalized alloy castings, and their use will no doubt increase as the prejudice against liquid quenching disappears.

TABLE V.—LOW-CARBON STEEL CASTINGS, WATER QUENCHED FROM 1600° F. (870 C.).

Chemical composition: manganese 0.60 to 0.90 per cent, silicon 0.25 to 0.35 per cent.

Drawing Temperature		Carbon, per cent	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Charpy Impact, ft-lb.	Brinell Hardnes Number
deg. Fahr.	deg. Cent.							
600	315	0.30	116 750	71 800	17.5	42.2	13.7	302
700	370	0.35	111 500	68 600	17.0	43.7	15.8	269
900	480	0.31	97 000	64 100	25.5	54.1	24.1	212
1000	540	0.33	102 100	69 100	21.5	49.5	20.8	217
1200	650	0.27	81 350	48 900	27.5	63.3	31.5	179

TABLE VI.—TABLE OF PROPERTIES OF A PLAIN CARBON-STEEL CASTING AVERAGE OF 80 TESTS.

	As Cast	Full-Annealed	Water-Quenched and Drawn	Per Cent Change After Full-Annealed	Per Cent Change After Quenched and Drawn
Tensile strength, lb. per sq. in.	74 100	75 000	80 000 to 125 000	+ 1.1	+12.6
Yield point, lb. per sq. in.	37 100	41 500	50 000 to 97 000	+12.0	+53.8
Elongation in 2 in., per cent	19.5	24.5	30 to 10	+30.8	+61.5
Reduction of area, per cent	31.0	46.2	65 to 200	+51.7	+124.1
Brinell hardness number	160	145	155 to 250	−8.3	+2.5
Izod impact, ft-lb	16	20	48 to 15	+23.5	+158.8
Endurance ratio	0.40	0.44	0.50	+10.0	+25.0

Acknowledgments:

Acknowledgment is made to the following persons for their kindness in furnishing data and information presented in this paper:

Richard Armstrong, Union Steel Casting Co.
George Batty, Steel Castings Development Bureau.
R. A. Bull, Electric Steel Founders' Research Group.
J. A. Capp, General Electric Co.
A. W. Gregg, Bonney-Floyd Co.
Fred Grotts, Continental Roll and Steel Foundry Co.
W. C. Hamilton, American Steel Foundries.

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[1] H. A. Mitchell, "Getting the Most out of Steel Castings," *The Iron Age*, October 2, 1930.

FUSION WELDING AS RELATED TO STEEL CASTINGS

By T. S. Quinn[1]

For at least a quarter of a century, fusion welding, as distinguished from the old-time plastic welding, has been employed by the steel foundryman for repairing small defects in his product not sufficiently serious to warrant condemnation. The author believes it was during the early part of the twentieth century that fusion welding was first performed in the steel foundry by means of thermit. Arc welding by means of a motor-generator set, substantially as it is performed today, was introduced to the steel foundry about twenty-three years ago, in what is now one of the plants of the General Steel Castings Corp. The author has been informed that the General Electric Co., as the result of investigations made by R. A. Bull, then General Superintendent of the Commonwealth Steel Co., designed and supplied the concern last named with a motor-generator set, by means of which the plant voltage of 220 was reduced to 80, for providing resistance to produce fusion economically for the repair of steel castings.

It is only within the last fifteen years that fusion welding has come into prominence. Naturally the product of iron and steel foundries has been materially affected by the extended application of fusion welding to engineering structures. It is well known that welded parts have superseded gray-iron castings for many industrial purposes, and it is a matter of common knowledge that weldings (a new, convenient term applied to structures formed by the fusion of connections) have had an important effect on the steel-casting industry. In some cases this influence has operated to the disadvantage of the individual steel foundry; in other instances the steel-casting shop has reaped direct advantages. In one respect the steel-casting industry as a whole has benefited greatly, through the stimulating example provided by designers of welded assemblages in emphasizing the economic advantage of structural simplicity.

Not until the proponents of fusion welding realized and made clear to the industrial world the fallacy of invariable adherence to familiar forms of construction, did the welding industry begin to profit greatly. In this respect welders made a contribution to engineering which had not previously been made, either by founders or by those operating shops where riveting was the medium of assemblage.

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[1] Treasurer, Lebanon Steel Foundry, Lebanon, Pa.

They realized that revision of design was essential for the economical employment of fusion fabrication as a substitute for riveted construction or for the integral casting, employed previously.

THE STEEL FOUNDER'S ATTITUDE MISUNDERSTOOD

There has been confusion in the minds of some engineers regarding the attitude of steel foundrymen toward welding. This has been due partially to the natural excess of enthusiasm of certain manufacturers of welding equipment, who thought for a time that a marked reduction would take place in the tonnages of all kinds of ferrous castings required for industrial purposes. Economies resulting from the substitution of some weldings for castings prompted the thought that parts fabricated by the fusion of joints would ultimately take the place of castings to an extent that would materially lower the output of the steel foundry.

The average steel foundryman, in fact, for many years has zealously kept himself informed of the results secured by arc and gas welding, because of his employment of such welding for reclamation purposes. Moreover, the producer of steel castings, as the natural result of the characteristics of the metal he makes, is always ductility-conscious, and he therefore has taken pains to determine not only the tensile strength typical of the metal in welded joints, but the percentages of elongation and reduction of area which, combined, constitute an acceptable index of ductility. He has realized that a tensile strength of 85 per cent of that in a casting made from common steel having a carbon content of say 0.28 per cent might be fully satisfactory or absolutely unsuitable for a given structural purpose, depending very largely on the amount of ductility in the welded connection.

With such considerations as these in mind, the conscientious steel foundryman has been unwilling to take a chance in welding a defect, if such salvaging involved an area of appreciable size in a member to be subjected to severe shock, or to frequent repetitions of serious stresses of any description. Those who make steel castings have not always been given credit for their desire, commercially inspired, to see the welding art developed to a point where, simultaneously, good values for tensile strength and for ductility may be obtained regularly in routine welding.

In still another respect the foundryman's attitude toward welding has been misunderstood, namely, in his advocacy of heat treatment for relieving internal stresses induced by welding. It is well known that heat treatment is desirable for eliminating the stresses set up when steel solidifies. Evidence of such cooling stresses is seen in the disconcerting behavior of certain castings before full-annealing or normalizing to relieve these stresses, which occasionally result in a rupture, accompanied by an explosive noise, of a large casting while subjected to external stresses of relatively insignificant degree. Since it is well known that the phenomena accompanying solidification of steel create these peculiar and sometimes disastrous internal stresses, it is but natural that the steel foundryman, contemplating the welding repair of vital members in a casting intended for severe service, should have in mind continuously such security as may be attained by a simple form of heat treatment. Arguments that have been advanced by foundrymen in favor of such treatment of welded steel parts, for the relief of cooling stresses, are properly founded on a knowledge of the behavior of metals.

EFFORTS TO MAKE DUCTILE WELDS

Fortunately, those who have directed intelligent efforts in the development of fusion welding by means of the arc and by the use of gas have made it practicable to obtain much more ductile welds than were ordinarily secured ten years ago. Placing great significance on ductility, the steel foundryman has had little interest in figures that have shown only a tensile strength in the welded joint comparable to, and sometimes superior to, that in some alloy grades of gray iron and in the grades of very soft carbon steel ordinarily used for structural purposes up to fifteen years ago. Since that time, there has been an increasing tendency to resort to higher carbon, manganese and silicon contents in carbon cast steels, resulting, when properly heat treated, in higher strengths accompanied by outstanding ductility and economical machineability. Within the same period of fifteen years, as is well known, there have been notable advances in the development of alloy steels for cast and wrought parts, providing combinations of strength and ductility that are most impressive.

The steel foundryman has been cognizant of the principal difficulty facing those who have tried to develop equipment and procedure that would materially reduce or completely eliminate the injurious effects of oxidation. Exposure of the liquefied steel to the atmosphere necessarily causes certain valuable elements present in the base metal and in the filler rods to oxidize to a varying extent. The oxidizable elements include carbon, manganese and silicon, which, in their combinations, tremendously influence physical behavior.

Among the more recent developments, ingeniously devised for preventing this atmospheric contact, is the blanketing of the welding area by means of hydrogen gas, also used in the atomic-hydrogen method, employing the electric arc for generating heat.

An effort to prevent atmospheric contact with the liquid metal formed by fusion has been made in another important direction, involving the special coating of filler rods. Some of the material in the coatings previously used resolves itself into slag at the fusing temperature. When rods are of suitable chemical composition and when the welding operation is skillfully performed, the slag resulting from the rod coatings partially excludes the atmosphere. The difficulty inherently existing in connection with this type of coated rod is in the increased amount of slag formed, which is liable to be entrapped in the weld metal, especially if the weld is of appreciable depth. The most recent and one of the most promising developments to minimize deterioration of the weld metal from slag and from oxidation consists in coating the filler rods with material that creates a reducing atmosphere during the fusing operation. The objective is to provide a protecting blanket of a non-slagging nature. Experiments along this line are being prosecuted with encouraging results. These and other researches have been carried on by those welding experts who have realized that one cannot reasonably expect in weld metal those physical characteristics that provide adequate resistance to fatigue and impact, unless there is present in such metal, uncontaminated by gas or slag inclusions, the proportions of those chemical elements which, in combination, give steel its unique, invaluable, composite property we call toughness.

As the result of intelligent effort zealously applied, there has been attained a gratifying approach to those conditions of homogeneity, chemical composition, and physical behavior which characterize ordinary or carbon steel. This partial achievement has given the properly formed, average welded joint, whether made by means of gas or electricity, adequate resistance to withstand the stresses applied to such joints, in parts applied for a great many purposes.

No unfavorable criticism is implied in pointing out that discretion should be used in drawing conclusions on the dependability of the fusion-made joint. A steel foundryman who has published numerous articles on this subject has convincingly emphasized the fact that the nature, degree and direction of the stresses to be exerted in service should always be carefully considered by the construction engineer; and that the latter should inform himself regarding the physical behavior of the weld metal in a connection selected as being representative.[1] For a great many purposes, such metal is entirely satisfactory. For many applications where certain stresses are applied with great severity and in directions that would be disadvantageous to the typical structure in weld metal, the fusion-made joint should be eliminated from consideration, and dependence should be placed on the integral piece of steel. Obviously, for a great many shapes, it is not feasible to provide such integral pieces of steel economically except by means of castings.

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[1] "Justifiable Uses of Welding," *Research Group News*, October, 1927, p. 148; "Fusion Welding Results Analyzed," *Research Group News*, April, 1931, p. 375; "Uses of Steel Castings as Affected by Welding," *Metal Progress*, February, 1931, p. 70.

DESIGN A COST FACTOR OF GREAT IMPORTANCE

Mention has been made of the helpful example welders have given founders, in respect to design. In justice to those foundrymen who have not been indifferent about low-cost construction, it is but fair to state that arguments presented to some consumers of castings for the economical simplification of design were fruitless until very promising claims were made to these same consumers, regarding the savings possible with fusion welding, associated with the redesign of the part under consideration. The author believes that many economies resulting from welding fabrication have come about from the redesigning incidental to the decision to employ fusion for making certain connections, rather than from the new method of assemblage. Putting it differently, if the foundryman had been permitted to simplify the design of the original casting so as to make it as cheaply as possible without sacrificing any desirable property or useful construction feature, the result obtained from the foundry would have been quite as satisfactory to the purchaser as the simple welded unit proved to be. It is human nature for the people generally to listen more attentively to claims made for the possibilities of a new process, than to the assertions regarding a well-known procedure. Novelty always excites interest.

TEST DATA

The author presents the results obtained from a number of tests in welding cast steel by various methods. Some of these test data have been procured under the author's direction; others have been submitted to him specifically for his discretionary use in the paper, by contributors who believe the information is accurate and based upon the best methods of various kinds in commercial use today.

Data Secured from Other Sources:

The author has no reason for discounting any of the data quoted. It is realized that, for certain purposes, these data would be more useful if they included statements making known the sources of information given the author. However, it has seemed that for the present purpose such information should be withheld, since discrimination made purely for the purpose of selecting what appeared to be accurate data had to be made, and since a contribution of this kind should not advertise the welding equipment or supplies of proprietary nature now being merchandised by a large number of concerns. It is believed that the data will be self-explanatory within these limitations.

All details reported to the author regarding analyses, heat treatments, etc., affecting the tests summarized have been included. In a few cases, averages only of groups of specimens have been stated, because the author did not have available the individual test data.

In summarizing the data for presentation, the author has used fictitious heat and specimen numbers, employing a consecutive order merely for the convenience of the reader.

TESTS OF CAST STEEL WELDED BY THE ARC METHOD

Report No. 1:

Bars Nos. 1 to 6.—Plates of plain carbon cast steel, 2 in. thick, having a carbon content of 0.30 to 0.35 per cent, were machined to form a double "V" of 45 deg. A current of 220 amperes was used. No peaning or hammering was done.

Bars Nos. 7 to 12.—Specimens welded under conditions similar to those existing when welding bars Nos. 1 to 6, except that larger electrodes and a current of 300 amperes with reversed polarity were used.

TENSION TESTS ON WELDED BARS. Annealed at 1650° F. after welding.

	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
No. 1	60 500	41 750	19.0	48.0
No. 2	61 375	43 375	20.0	52.8
No. 3	61 750	38 375	21.0	46.9
No. 4	61 250	39 500	22.5	61.3
No. 5	55 625	35 875	11.5	34.7
No. 6	59 625	38 500	17.0	37.6
Average	60 020	39 562	18.5	46.8
No. 7	58 625	35 625	20.0	45.7
No. 8	56 500	36 750	16.5	41.6
No. 9	57 000	35 000	20.5	46.9
No. 10	59 000	35 000	17.0	34.[illegible]
No. 11	57 250	39 250	20.0	42.8
No. 12	57 250	36 625	21.5	42.8
Average	57 604	36 375	19.2	42.3

Report No. 2:

Experiments were conducted in welding carbon cast steel with the arc in conjunction with a protecting envelope consisting of hydrogen and other gases, including 15 per cent propane. Ordinary uncoated electrodes were used. This method is similar in some respects to the atomic hydrogen method.

Tension Tests on Welded Bars. Annealed at 1650° F. after welding.

	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
No. 13	83 750	61 625	23.5	50.0
No. 14	85 560	63 310	18.5	31.5
Average	84 655	62 467	21.0	40.7

TESTS OF CAST STEEL WELDED BY THE OXY-ACETYLENE METHOD

Report No. 3:

Tension Tests. Normalized 1 hour at 1650° F., and drawn 1 hour at 1200° F.

Chemical composition, heat No. 200: carbon 0.28 per cent, manganese 0.71 per cent, silicon 0.39 per cent.

Unwelded Bar		Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent
No. 15	..	74 000	41 000	25.0	40.0
Welded Bars	Rod				
No. 16	A	62 200	37 850	12.0	31.6
No. 17	A	60 850	37 350	14.0	42.2
No. 18	A	60 850	37 350	13.0	35.7
Average	A	61 300	37 520	13.0	36.5
No. 19	B	60 850	35 400	15.0	45.5
No. 20	B	57 150	36 100	15.5	52.6
No. 21	B	57 300	35 400	17.0	57.0
Average	B	58 430	35 630	15.8	51.7

Report No. 4:

Tension Tests. Normalized at 1650° F., heated 2 hours.

Chemical composition, heat No. 201: carbon 0.35 per cent, manganese 0.69 per cent, silicon 0.35 per cent, phosphorus 0.033 per cent, sulfur 0.040 per cent.

	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Reduction of Area, per cent
Unwelded Bars			
No. 22	88 400	50 250	30.8
No. 23	87 300	48 600	37.3
Average	87 850	49 425	34.0
Welded Bars			
No. 24	78 900	46 700	22.0
No. 25	71 300	44 700	25.4
No. 26	77 800	44 700	27.8
No. 27	76 850	46 700	22.0
No. 28	78 800	47 300	31.3
Average	76 730	46 020	25.7

Report No. 5:

Experiments were conducted on specimens from one heat of plain carbon cast steel to ascertain the effects of heat treatment on the ductility of steel deposited in welding a given base metal by a given procedure. Results are shown in the figures for groups I, II and III.

Tension Tests on Welded Bars.

	Tensile Strength, lb. per sq. in.	Yield Point, lb. per sq. in.	Reduction of Area, per cent
Group I. Results on material as welded, without heat treatment.			
No. 29	60 400	45 850	10.4
No. 30	66 800	44 350	23.4
No. 31	65 300	44 600	11.2
Average	64 166	44 933	15.0
Group II. Heated at 1650° F. for 1 hour after welding, and cooled in air.			
No. 32	67 150	44 100	25.9
No. 33	67 600	44 100	27.4
No. 34	67 800	46 400	28.8
Average	67 516	44 866	27.3
Group III. After welding, bars slowly heated to 1650° F. cooled in air, reheated to 1200° F. for 1 hour and cooled in furnace.			
No. 35	62 200	37 850	31.7
No. 36	60 850	37 350	42.2
No. 37	60 850	37 350	35.7
No. 38	60 850	35 400	45.5
No. 39	57 150	36 100	52.6
No. 40	57 300	35 400	57.0
Average	59 866	36 575	44.1

Report No. 6:

TENSION TESTS. Normalized and drawn.

Chemical composition, heat No. 202: carbon 0.35 per cent, manganese 1.36 per cent, silicon 0.44 per cent, phosphorus 0.035 per cent, sulfur 0.039 per cent.

UNWELDED BARS	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	REDUCTION OF AREA, PER CENT
No. 41	97 300	58 400	38.8
No. 42	97 700	57 550	40.6
Average	97 500	57 975	39.7

WELDED BARS. Normalized and drawn after welding with rods containing approximately 0.40 per cent carbon, 1.50 to 1.80 per cent manganese, and some molybdenum.

No. 43	96 600	60 450	24.1
No. 44	98 200	59 400	55.0
No. 45	94 800	58 600	29.5
No. 46	98 250	57 500	20.6
Average	96 962	58 987	32.3

Report No. 7:

Five carbon steel welded bars gave results which, when averaged, showed a yield point of 93 per cent, and a tensile strength of 87 per cent, of the properties in the unwelded material. The percentages of elongation in 2 in. ranged from 8 to 11, and the percentages of reduction of area ranged from 22 to 31, in the welded bars. These bars had been normalized at 1600° F. after welding.

Five medium manganese steel welded bars gave results which, when averaged, showed a yield point of 120 per cent, and a tensile strength of 99 per cent, of the properties in the unwelded steel. The percentages of elongation ranged from 12.5 to 25, and the percentages of reduction of area ranged from 17 to 55, in the welded bars. These bars had been normalized at 1550° F. after welding.

TESTS OF CAST STEEL WELDED BY THE ATOMIC-HYDROGEN METHOD

Report No. 8:

Eight carbon steel welded bars gave results which, when averaged, showed a yield point of 93 per cent, and a tensile strength of 81 per cent, of the properties in the unwelded material. The percentages of elongation ranged from 8 to 10, and the percentages of reduction of area ranged from 19 to 33, in the welded bars. These bars had been normalized at 1600° F. after welding.

Twelve medium manganese steel welded bars gave results which, when averaged, showed a yield point of 96 per cent, and a tensile strength of 88 per cent, of the properties in the unwelded material. The percentages of elongation ranged from 5.5 to 16, and the percentages of reduction of area ranged from 16 to 55, in the welded bars. These bars had been normalized at 1500° F. after welding.

Report No. 9:

TENSION TESTS ON WELDED BARS. Normalized 40 minutes at 1650° F. and drawn 1 hour at 1275° F., after welding with rod from steel made in heat No. 203.

Chemical composition, heat No. 203: carbon 0.27 per cent, manganese 0.73 per cent, silicon 0.42 per cent.

	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
No. 47	62 000	38 250	25.0	63.5
No. 48	61 250	39 000	22.7	51.9
No. 49	61 000	39 000	21.1	55.5
No. 50	61 750	38 750	25.8	59.2
Average	61 500	38 750	23.7	57.5

Report No. 10:

TENSION TESTS. Normalized at 1600° F., heated 2 hours.

Chemical composition, heat No. 204: carbon 0.35 per cent, manganese 0.69 per cent, silicon 0.347 per cent, phosphorus 0.033 per cent, sulfur 0.040 per cent.

UNWELDED BARS	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
No. 51	88 400	50 250	22.0	30.8
No. 52	87 300	48 600	28.0	37.3
Average	87 850	49 425	25.0	34.0

WELDED BARS. Welding rod contained 0.18 per cent carbon, 1.40 per cent manganese, and 0.50 per cent silicon.

	AMPERES				
No. 53	76	70 500	42 850	9.0	31.2
No. 54	76	65 250	41 450	8.0	23.4
No. 55	80	71 200	48 800	9.0	26.5
No. 56	80	73 000	47 150	10.0	28.5
No. 57	86	72 800	49 900	12.0	22.3
No. 58	86	70 750	49 000	8.5	32.8
No. 59	70	72 300	48 900	10.0	22.7
No. 60	70	70 100	47 100	10.0	18.8
Average		70 737	46 868	9.6	25.8

Report No. 11:

TENSION TESTS.

Chemical composition, heat No. 205: carbon 0.355 per cent, manganese 1.40 per cent, silicon 0.47 per cent, phosphorus 0.035 per cent, sulfur 0.039 per cent.

UNWELDED BARS. Normalized at 1650° F., and drawn at 500° F. for 12 hours.

	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA. PER CENT
No. 61	99 450	61 150	28.0	56.0
No. 62	98 750	58 950	28.0	57.3
Average	99 600	60 050	28.0	56.6

WELDED BARS. Normalized at 1650° F. and drawn at 500° F., before welding. Normalized at 1525° F., after welding. Welding rod contained 0.25 per cent carbon, 1.50 per cent manganese, 0.40 per cent silicon, and 0.40 per cent molybdenum.

	AMPERES				
No. 63	76	87 350	59 800	10.5	28.5
No. 64	76	86 000	59 900	8.0	15.9
No. 65	80	86 900	58 950	12.5	30.2
No. 66	80	86 950	57 900	9.0	33.4
No. 67	86	92 250	58 200	12.0	29.8
No. 68	86	91 200	56 950	11.0	27.5
No. 69	70	91 250	61 000	12.0	26.8
No. 70	70	80 250	59 000	5.5	8.5
Average		87 768	58 962	10.1	25.1

To ascertain the influence of a heat treatment on the welded material which has the effect of "aging" on unwelded steel, four additional bars from heat No. 205, welded by the atomic-hydrogen method, with rod material of the composition used for bars Nos. 53 to 60, were heated, after welding, at 1525° F., machined, and drawn at 500° F. for 12 hours.

	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
No. 71	82 600	56 300	12.5	39.7
No. 72	96 750	59 500	12.5	35.7
No. 73	81 850	53 250	12.0	35.7
No. 74	82 350	50 600	16.0	54.7
Average	85 887	54 912	13.3	41.4

Report No. 12:

TENSION TESTS ON WELDED BARS. Annealed at 1650° F. after welding.

Chemical composition, heat No. 206: carbon 0.32 per cent, manganese 1.25 per cent, silicon 0.32 per cent, molybdenum 0.33 per cent, phosphorus 0.033 per cent, sulfur 0.007 per cent.

	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
No. 75	81 750	45 000	23.5	50.0
No. 76	82 125	45 625	20.5	47.7
No. 77	77 125	45 000	16.5	41.3
No. 78	79 250	44 125	21.0	50.0
No. 79	79 125	45 500	18.5	47.0
Average	79 875	45 050	20.0	47.2

Report No. 13:

TENSION TESTS.

Chemical composition, heat No. 207: carbon 0.38 per cent, manganese 1.24 per cent, silicon 0.42 per cent, chromium 0.74 per cent, molybdenum 0.33 per cent.

	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
UNWELDED BAR. Normalized at 1650° F., and drawn at 1275° F.				
No. 80	103 000	70 500	21.9	31.1
WELDED BAR. Normalized at 1650° F., and drawn at 1275° F., after welding with bar cast in heat No. 208.				
No. 81	76 000	62 500	4.7	14.1
No. 82	70 250	64 000	6.3	24.8
Average	73 125	63 250	5.5	18.4

Report No. 14:

TENSION TESTS ON WELDED BARS. Full-annealed 2 hours at 1650° F., after welding with rod cast in heat No. 208.

Chemical composition, heat No. 208: carbon 0.44 per cent, manganese 0.55 per cent, silicon, 0.64 per cent, chromium 18.22 per cent, copper 0.91 per cent.

	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
No. 83	90 700	53 250	10.2	11.3
No. 84	85 900	52 250	8.6	9.8
No. 85	89 750	54 000	8.6	8.6
No. 86	92 000	55 000	9.4	9.3
Average	89 587	53 625	9.2	9.7

Report No. 15:

TENSION TESTS ON WELDED BARS. Normalized at 1650° F., and drawn at 1275° F., after welding with 2 grades of rods.

Chemical composition, heat No. 209: carbon 0.30 per cent, manganese 1.32 per cent, silicon 0.45 per cent.

	ROD[a]	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
No. 87	C	65 500	41 000	17.2	39.4
No. 88	C	65 500	41 500	18.5	51.4
No. 89	D	81 500	48 500	18.5	57.5
No. 90	D	81 500	48 500	11.7	25.1

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[a] Rod C was cast in heat No. 209. Rod D was rolled and contained 0.47 per cent carbon, 1.98 per cent manganese, 0.56 per cent silicon, 0.020 per cent phosphorus and 0.020 per cent sulfur.

Data from Tests Made Under Author's Direction:

Many experiments have been conducted at the plant of the Lebanon Steel Foundry, and elsewhere for this plant, extending over a period of several years, to ascertain the kinds of equipment, supplies, voltages, ampereages, gas pressures, etc., to employ selectively for most effectively welding steel castings of widely varied compositions.

A few of the results obtained at the foundry mentioned are indicated below; not, however, with the claim that they represent, in any instance, the most effective welding capable of being done with the material in hand, but with the hope that they may be helpfully suggestive. Limitations of space left after reporting results secured in other plants and laboratories, prevent elaboration on the tests made in the foundry with which the author is connected.

TESTS OF CAST STEEL WELDED BY THE ARC METHOD

Report No. 16:

TENSION TESTS ON WELDED BARS. Coated welding rod contained 0.13 per cent carbon, 0.46 per cent manganese and 0.04 per cent silicon, no special alloys being found on analysis.

Chemical composition, heat No. 210: carbon 0.27 per cent, manganese 0.78 per cent, silicon 0.38 per cent.

	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
Normalized 40 minutes at 1675° F., and drawn 1 hour at 1310° F., after welding with coated rod.				
No. 91	54 000	35 700	18.8	53.3
No. 92	52 750	35 500	20.3	59.8
No. 93	53 250	34 250	16.4	48.8
No. 94	53 500	39 000	17.9	57.3
Average	53 375	36 250	18.3	55.1
Oil quenched after heating 1 hour at 1650° F., and drawn 1 hour at 1000° F.; all following preliminary normalization 40 minutes at 1675° F.				
No. 95[a]	71 520	51 450	14.8	42.2
No. 96	70 000	51 960	12.5	40.7
Average	70 760	51 705	13.6	41.4

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[a] Analysis of weld metal showed 0.06 per cent carbon, 0.33 per cent manganese and 0.17 per cent silicon.

Report No. 17:

TENSION TESTS ON WELDED BARS. Normalized 1 hour at 1700° F., and drawn 1 hour at 1275° F., after welding with carbon steel, rod *E*, and with alloy steel, rod *F*, both rods being coated.

Chemical composition: heat No. 211, carbon 0.29 per cent, manganese 0.74 per cent, silicon 0.38 per cent; heat No. 212, carbon 0.30 per cent, manganese 1.33 per cent, silicon 0.39 per cent.

HEAT	BAR	ROD	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
No. 211	No. 97	E	67 250	43 250	14.8	19.9
No. 211	No. 98	E	67 250	42 750	17.2	42.2
No. 211	No. 99	F	65 250	42 250	15.6	39.1
No. 211	No. 100	F	66 750	45 000	17.2	40.1
No. 212	No. 101	E	67 250	39 000	14.1	27.5
No. 212	No. 102	E	65 500	40 500	15.6	43.4
No. 212	No. 103	F	67 000	41 250	14.8	44.9
No. 212	No. 104	F	66 000	41 500	14.1	36.0

TESTS OF CAST STEEL WELDED BY THE OXY-ACETYLENE METHOD

Report No. 18:

TENSION TEST. Normalized 1 hour at 1650° F., and drawn 1 hour at 1200° F.

Chemical composition, heat No. 213: carbon 0.25 per cent, manganese 0.70 per cent, silicon 0.35 per cent

UNWELDED BAR		TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
No. 105		72 000	40 000	29.0	48.0
WELDED BARS	ROD				
No. 106	A	68 750	42 000	14.5	39.4
No. 107	A	69 500	44 000	16.5	49.2
No. 108	A	43 500	43 500	16.5	46.6
Average	A	68 915	43 167	15.8	45.1
No. 109	B	63 000	43 000	16.0	55.0
No. 110	B	65 250	43 500	17.5	58.1
No. 111	B	66 500	46 000	17.5	57.1
Average	B	64 915	44 167	17.0	56.9

Miscellaneous Comments on Tests Made with the Cooperation of the Author:

The author has reported results made known to him, obtained at numerous plants and laboratories, to give a comprehensive idea of what is probably the most effective welding done today on steel castings. It seems unneccessary to supplement the foregoing information by figures obtained from a great many other tests made by the company with which the author is connected. Generally speaking, the test results in this paper indicate results from the employment of good equipment, competent operators, and discrimination in the selection of current, gas pressures, etc., and welding rods in particular.

To convey a clear idea of differing results obtained by the use of rods of the many kinds on the market, there will be found below a tabulation resulting from tests made under the author's general direction, showing averages of results when welding cast steel of ordinary composition. For obvious reasons the identities of the rod manufacturers are not disclosed. The author's experience indicates that when welding with gas, results as divergent as those found below are obtained, according to the nature of the rod employed:

AVERAGES FROM SOME TESTS IN ARC WELDING 0.28 PER CENT CARBON CAST STEEL, WITH VARIOUS WELDING RODS.

Bars normalized and drawn after welding.

ROD	TENSILE STRENGTH, LB. PER SQ. IN.	YIELD POINT, LB. PER SQ. IN.	ELONGATION IN 2 IN., PER CENT	REDUCTION OF AREA, PER CENT
No. 1	65 000	41 875	15.4	40.0
No. 2	66 810	41 375	15.4	33.2
No. 3	53 375	36 250	18.3	55.1
No. 4	52 250	39 420	10.4	22.8
No. 5	51 650	39 435	8.8	26.2
No. 6	44 785	32 165	7.3	19.7
No. 7	46 915	37 670	6.0	13.1

It seems to be demonstrated that the best straight arc welding can be done with specially coated rods. There are several varieties of these, produced by competitive concerns, which are capable of yielding good results. Generally, if not always, it is found desirable to employ reversed polarity when applying a coated rod. The poorest welds indicated in the preceding tabulation were made with bare welding rods.

At times information has been sought regarding the machineability of weld metal. Many Brinell readings were made at the Lebanon Steel Foundry to ascertain the average condition of hardness in the weld metal, in the zone immediately adjacent to the weld, and in the casting proper. The tests included readings prior to, and after, heat treatment; after welding by the oxy-acetylene, the atomic-hydrogen, and the arc methods. The arc welding tests included bare and coated rods.

Briefly summarizing, tests on cast steel with an average composition of 0.25 per cent carbon, 0.75 per cent manganese and 0.38 per cent silicon showed the following average Brinell hardness readings:

	AVERAGE BRINELL HARDNESS NUMBERS		
METHOD OF WELDING	BEFORE HEAT TREATMENT	AFTER A DRAW AT 1275° F.	AFTER A NORMALIZING TREATMENT FOLLOWED BY A DRAW
Arc	127	121	118
Oxy-acetylene	125	108	102
Atomic-hydrogen	155	137	110

GENERAL COMMENTS

To prevent occupying too much space with comments as to fractures, references to these have been omitted from the tabulations. It may be said generally that the fracture of a butt-welded piece of cast steel occasionally discloses small gas cavities and particles of slaggy matter. The extent to which porosity and non-metallic material are present in weld metal seems now to be largely dependent on the nature of the rod and the skill of the operator. With a careless workman using good rod material, or a careful workman using inferior rod material, gas cavities and non-metallic enclosures are apt to be found in varying degree, irrespective of the method employed for welding and irrespective of the correctness of voltages, ampereages, gas pressures, and other factors important to maintain, according to the method utilized for producing fusion. The complete elimination of gas appears to be very difficult to attain.

It is gratifying to the users of welded material as well as to the makers of such material, to realize that good welds are capable of being made by the arc method, by the oxy-acetylene method, and by the atomic-hydrogen method. This fact is indicated by the figures quoted in this paper.

The principal purpose in presenting the foregoing test data has been to show the extent to which serviceable welds may be made with available facilities. The tension test values demonstrate the possibilities when employing what are believed to be modern equipment and proper procedure, including the important factor of the human element, for it is highly essential that the operator be properly directed and conscientiously inclined. The results given are not claimed by the author to represent average practice. He is in no position to ascertain and comprehensively to evaluate the results of typical practice in all plants welding steel castings.

Examination of the data might, without further explanation, convey the idea that steel foundrymen are concerned only with the values of welds obtained in tension testing. This is not the case. Foundrymen are greatly interested in the growing technical literature regarding fatigue, shock, corrosion, and other comparative tests of unwelded and welded steels, which naturally have been made mostly on wrought steels and have resulted in instructive information that is being applied in the best engineering practice. Thus, a considerable amount of data is now available as a guide for estimating resistance to shocks and to fatigue in properly welded portions of fabricated structures. For the purpose of the present discussion it is regrettable that there have not been published or reported to the author sufficient data regarding impact, fatigue, and certain other tests on welded cast steel, to make feasible the inclusion of such figures in this paper. It is hoped that conclusive information relating to other than tension tests, made on welded steel castings, may be available soon for the information of engineers.

It is proper here to point out that there is an increasing dependence on the bend test for determining the ductility of welded joints.

In this test, after bending, the extension of the deposited metal is measured, and the percentage of this elongation is recorded. This may ultimately prove to be the most satisfactory method of ascertaining the extent to which welded metal will stretch, this being a recognized indication of ductility. At the present time, on account

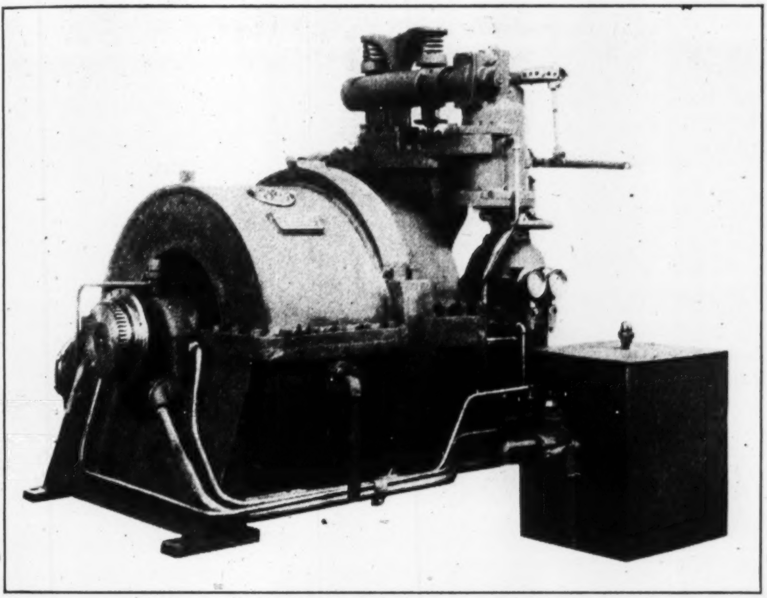

FIG. 1.—Steam Turbine Having Steel Castings Welded to Rolled Steel Parts.
Photograph supplied by General Electric Co.

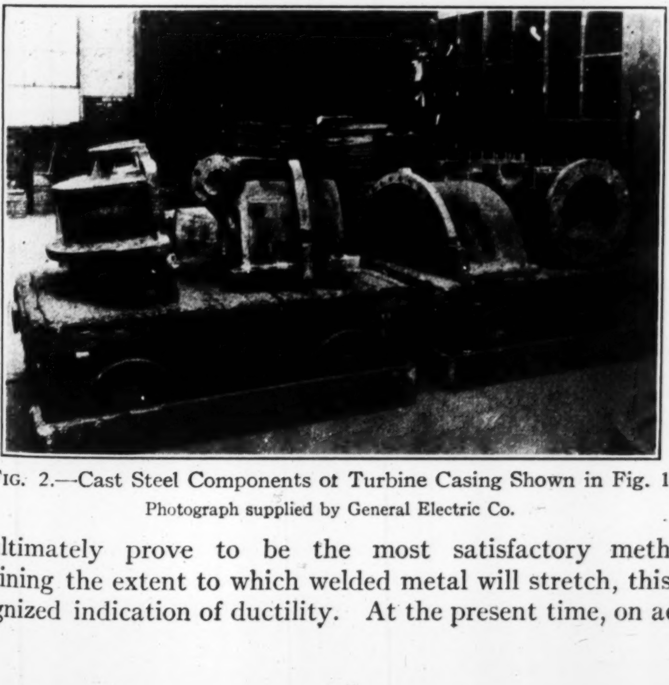

FIG. 2.—Cast Steel Components ot Turbine Casing Shown in Fig. 1.
Photograph supplied by General Electric Co.

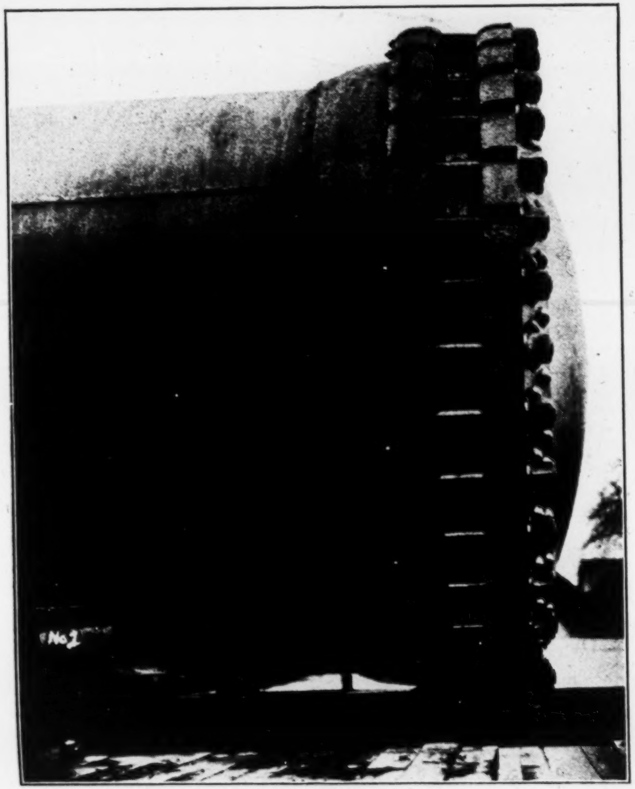

FIG. 3.—Ring Casting of Medium Manganese (1.50 per cent) Steel Welded to Rolled Shell (1 in. thick) of Creosoting Retort for Railroad Ties.

Photograph supplied by Linde Air Products Co.

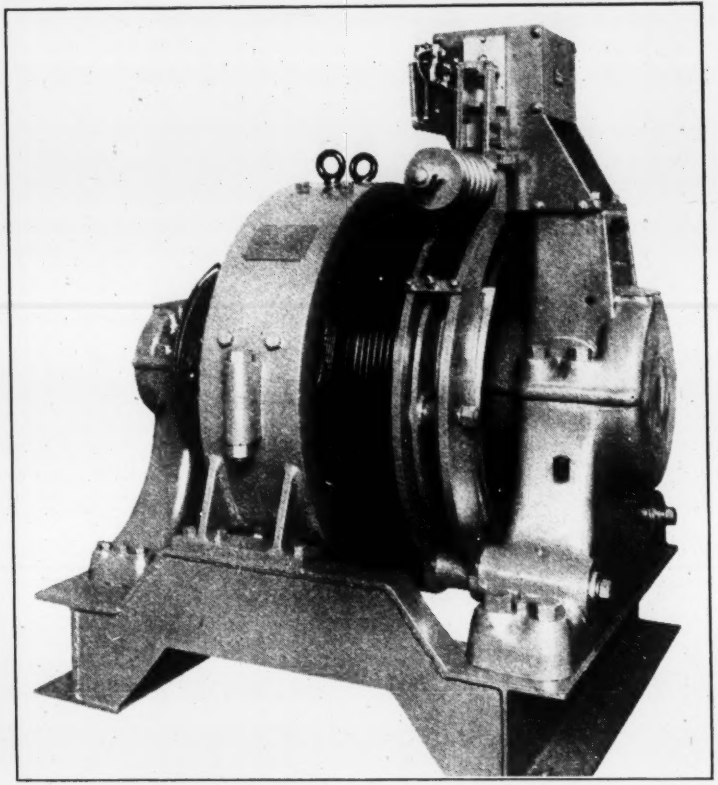

FIG. 4.—Elevator Motor Having Composite Frame Including Steel Castings Welded to Rolled Steel Parts.

Photograph supplied by General Electric Co.

of the almost universal dependence on the tension test, the latter must be relied upon as the most satisfactory basis for comparison of data reported from different laboratories. The bend test, obviously, has the distinct advantage of application in many shops where no tension testing machines are available.

Some experiments were made under the author's direction, in determining the elongation by means of the bend test method. Butt welds of cast steel showed in some cases, an elongation amounting to 45 per cent. It is not proper to compare this value with the percentage of elongation as determined by the tension test. The figures are not comparable with each other.

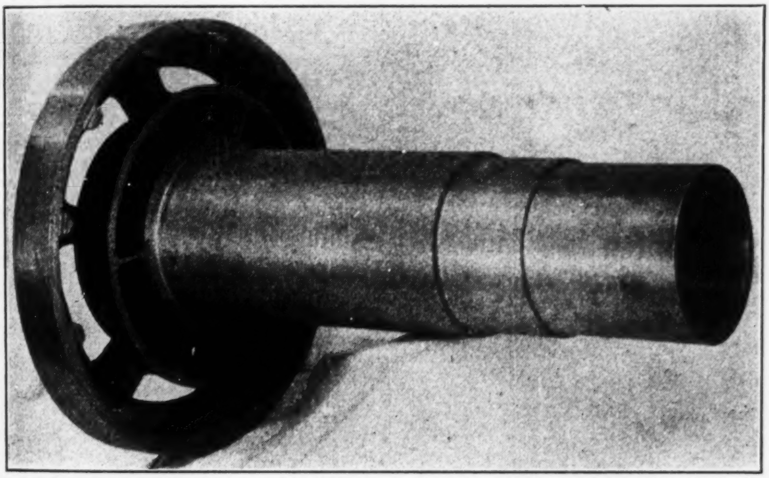

FIG. 5.—Armature Spider for Railway Motor Having Steel Casting Welded to Seamless Steel Tube.
Photograph supplied by General Electric Co.

It is well to give a word of caution against dependence alone on averages in evaluating laboratory tests of welded specimens. While very valuable, averages do not tell the whole story. The extent of deviation from the average is a vital factor to the engineer, who would not be justified in selecting for a highly important application a part which might, because of properties appreciably below the average, result in a serious hazard. Consistency of results is essential for certain uses.

X-rays, gamma-rays and magnetic testing afford means of obtaining useful information about fusion welds. Obviously, the first two methods are commercially practicable only in the case of highly important applications, where the cost of testing is a small factor. The better chance for the commercial use of such methods for testing welded objects would seem to be where welding is done on a large scale, involving many pieces of the same kind, as in fabrication on a production basis. The utility of X-ray or gamma-ray examination in some such instances might be practicable in guiding the manufacturer in the selection of the best procedure, following the examination of pilot or experimental castings, before starting regular production. Such a practice would, of course, find its greater feasibility in connection with comparatively large parts, the cost of which would prompt hesitation in making machining or other destructive tests.

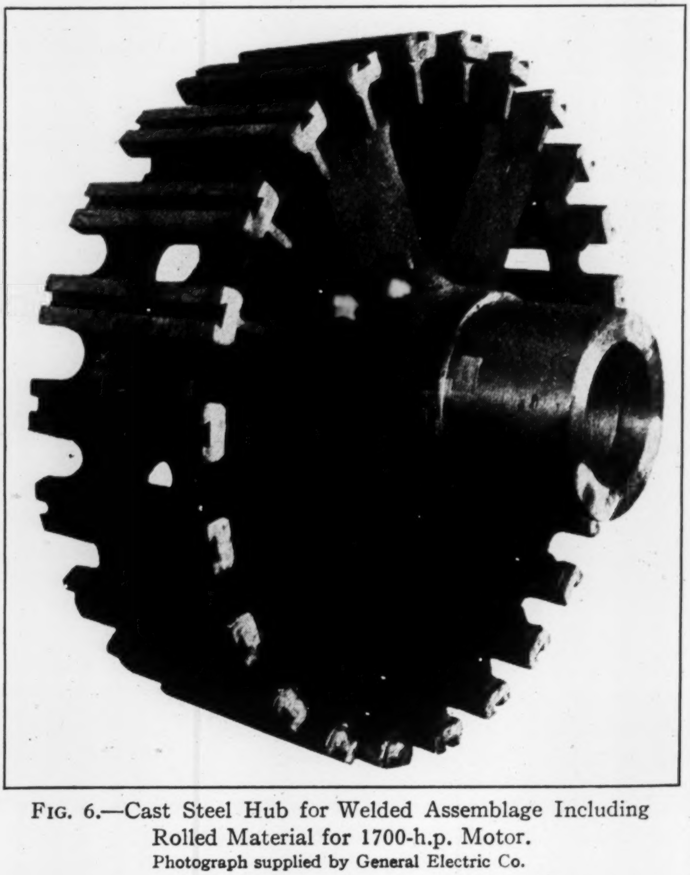

FIG. 6.—Cast Steel Hub for Welded Assemblage Including Rolled Material for 1700-h.p. Motor.
Photograph supplied by General Electric Co.

Mention has been made of the extent to which fusion welding has been employed advantageously in connecting steel castings to wrought steel parts. Those engineers who have studied welding from an economic standpoint perceive the fallacy of forming by fusion fabrication many intricate portions of assemblages, some parts of which lend themselves nicely to welding fabrication, by shape, by number of pieces wanted, and by intended use.

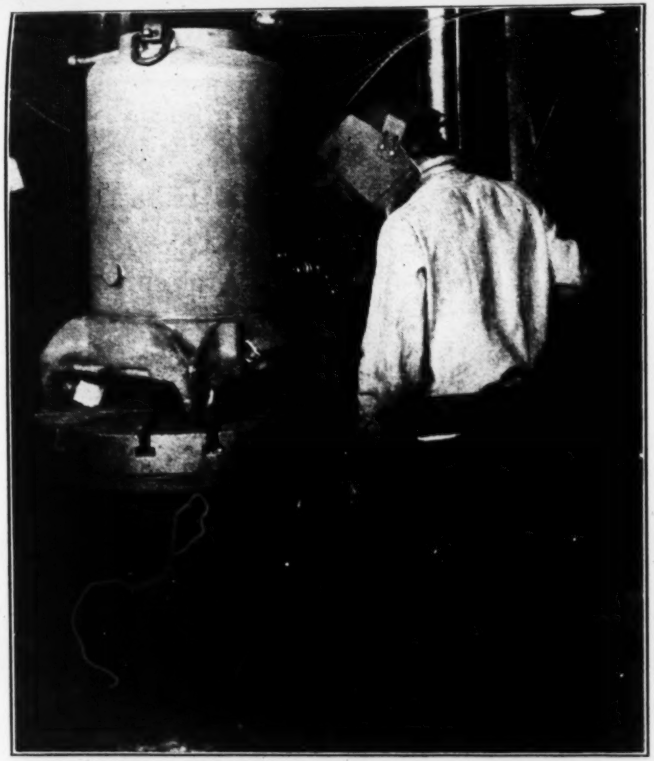

FIG. 7.—Cast Steel Top Being Fused to Rolled Steel Tank, with Equipment for Welding on a Production Basis.

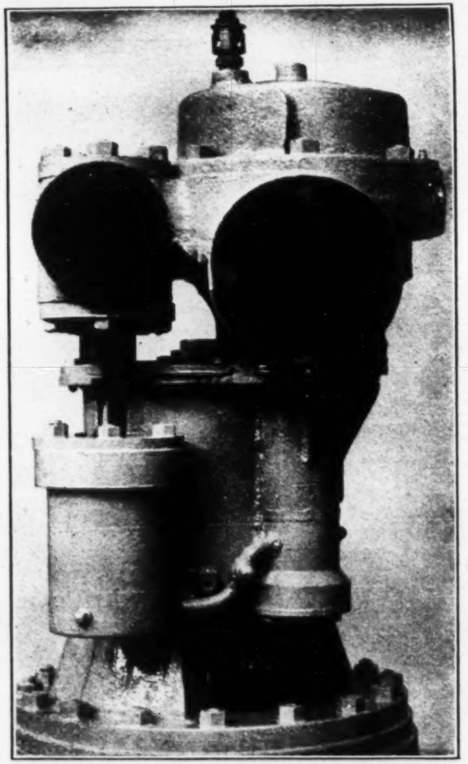

FIG. 8.—Welded Combination of Steel Castings and Plate Construction Used in Steam Turbine.

Photographs supplied by Westinghouse Electric and Manufacturing Co.

It is believed that a number of illustrations showing the employment of steel castings in such composite construction will convey the best idea of its utility. Figures 1 to 9 with their captions will probably be sufficiently explanatory without textual elaboration. It will be noted that both gas welding and arc welding have been employed. A great many cast steel parts have been used as portions of composite assemblages which have been applied successfully, which cannot be illustrated, for lack of space.

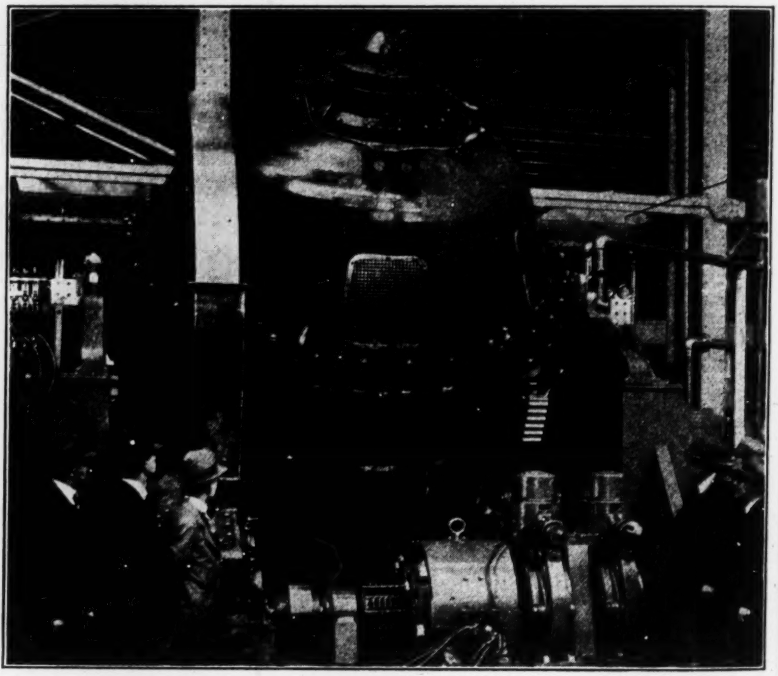

FIG. 9.—Ship Gyroscope Constructed of Rolled-Steel and Steel Castings Welded Together.

Photograph supplied by Westinghouse Electric and Manufacturing Co.

The author hopes his explanations will demonstrate that the steel foundryman happens to occupy what might be said to be a "middle ground" position in regard to welding. It is a position that combines long familiarity with this interesting art, with appreciation of the fact that steel castings have been used for certain purposes in the past where welded structures employing nothing but rolled shapes are now employed most economically. The discouraging aspect of this from the foundryman's viewpoint is counteracted by the realization of his ability to cast intricate shapes successfully for many purposes, enabling him to cooperate with the welding engineer, to the end that composite structures may be produced to the best economic advantage for the consumer.

Emphasis has been given to the fact that engineers are not yet justified in placing dependence on a welded joint for the most severe stresses to which certain parts are subjected in industrial applications. In one other respect is the engineer's consideration required, namely, the difficulty of successfully welding many varieties of alloy steel parts, both as to the homogeneity of the fused joint and as to the physical characteristics in the joint, gaged by the properties in the base metal when the latter is made from a special variety of steel. Much intelligent work has been performed by welding experts in the effort to develop in weld metal a fair approach to the chemical composition of alloy steel that has been welded. Progress has been made in this direction in connection with certain kinds of alloy steels. For example, special welding rods are used for parts made from austenitic manganese steel. But, among other problems, that of liquefying each of a great many grades of alloy steel without changing the proportion of each of several significant elements in the composition, is an extremely difficult one to solve. It will probably represent, for some time to come, a barrier against the very extended use of welding those parts of many grades of alloy steel which are serviceable largely in proportion to the special nature of their chemical composition.

A final comment is appropriate to make regarding the various details that need careful consideration in connection with the use of the arc or the employment of gas. Considerable intelligent study has been given to such matters by competent engineers, who have made sufficient tests (chiefly on wrought steels) to justify sound recommendations as to composition, coating, and diameter of rod; amperage of current; position and character of electrode; design of fillet connection; pressure and admixture of gas; nature of burner tip; and other factors that determine the quality of weld metal. These welding experts have also obtained and published valuable information regarding the best practices to employ when welding numerous varieties of alloy steel, including those in the high alloy classification. There is, all told, much information available in current literature on this interesting subject. It is natural that most of it should have significance particularly for those who depend on or contemplate fabrication in uniting rolled steel parts by fusion. If the author has been able to throw light on the subject of welding as related to the product of the steel foundry, he will have accomplished his purpose, especially if his contribution should prompt others to contribute information through the discussion of this paper.

DISCUSSION

MR. J. H. HALL.[1]—An important point was made by Mr. Quinn, namely, that if people who are now designing castings to form parts of complete welding assemblies had been willing to give attention to re-designing the castings in the first place, they would not have needed to resort to welded assemblies. That is something that all makers and all users of castings should consider.

It seems to me too that such data as Mr. Quinn has presented on the reliability of welds between cast members and other cast members, and between cast members and rolled members, will help us a lot in eliminating the fears of those who are so frightened when we want to make a small weld, not to attach the casting to another casting or to a rolled section, but to hold together the two sides of a small defect in the casting. It will not be long, I hope, before some of the absurdly restrictive specifications regarding the welding of castings will be removed and we will no longer have to get the inspector to look at a casting in the green state and ask his permission to weld up trifling defects.

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[1] Technical Assistant to President, Taylor-Wharton Iron and Steel Co., High Bridge, N. J.

EMBRITTLEMENT OF HOT-GALVANIZED STRUCTURAL STEEL[1]

By Samuel Epstein[2]

I. Introduction

Except for some slight consideration of galvanized electrical transmission line hardware, this investigation has been confined to the study of embrittlement in hot-galvanized structural steel angles such as are used in transmission towers.

Rarity of Embrittlement:

Such a report as this, since it must necessarily dwell at length on the subject of embrittlement, might tend to create the impression that embrittlement failures are common. It should, therefore, be stated at the outset that, on the contrary, they are extremely rare. In the 22 months between the start of this study and the date of transmitting this report, not a single failure of a galvanized structural steel tower due to embrittlement has come to light. The only known authenticated case of such a failure took place before the study started, and occurred in a heavy, punched angle during erection of a transmission tower. This angle was included in the present study. A careful scanning of the literature has disclosed no report or accounts of such failures.

History:

In August, 1927, a shipment of galvanized transmission tower steel was being unloaded in the Chicago district, when an angle fell from a railway car upon the ground and broke through some of the holes. Chemical analysis was said to show that bessemer steel had been mixed in with the lot of open-hearth steel by mistake. However, it was alleged that some open-hearth angles from the same consignment, broken through the holes by bending, also gave brittle fractures. No samples from this shipment had been retained, so that none of this material was available for use in this study, nor have any quantitative data on the properties of the angles been submitted. The various qualitative statements and the opinions put forth as to the possible causes for the behavior of this particular shipment were couched in such general terms as to throw no real light on the problem.

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[1] A report by Battelle Memorial Institute on an investigation sponsored by Subcommittee X on Embrittlement Investigation, Committee A-5 on Corrosion of Iron and Steel, American Society for Testing Materials.

[2] Metallurgist, Battelle Memorial Inst., Columbus, Ohio.

The need for first-hand, quantitative data was brought out through this incident. The alarm engendered by it and by the failure of the transmission tower during erection, referred to above, brought about the institution of this research.[1]

Defining Embrittlement:

In dealing with this sort of brittleness, that is, fracture with little or no deformation, it must be clearly understood that the embrittlement is narrowly localized about the hole. Away from the hole, the body of the steel, even in an "embrittled" angle, is fully ductile, both before and after galvanizing, as is proved by tension, bending, and notched-bar impact tests.

The problem of deciding the limiting amount of deformation, below which a break should be classed as brittle, is not an easy one, considering the complicated conditions introduced by the "notch effect" of the hole. This effect will vary with the size and location of the hole as related to the thickness and size of the angle, and above all with the manner of making the hole—whether it is punched, sub-punched and reamed, or drilled. One must naturally be content with less deformation about the hole in an angle than occurs at the fracture in the ordinary tension specimen. One way to attack the problem of defining embrittlement is to do a good deal of testing about the hole, to see what can be and generally is obtained in good quality commercial steel, and then set a fair limit with this value in mind. Another method would be to secure expert engineering opinion as to how much ductility is needed in a tower from the standpoint of an engineering standard of adequate safety. Both methods lead to similar conclusions.

Need for Ductility in Towers:

In a tower any danger from lack of ductility lies chiefly during its erection. Once the tower is up, no great amount of ductility would seem to be called for under normal conditions, although a certain minimum is required because of the risk of the elastic limit being exceeded locally in the structure and the necessity of providing for some redistribution of stress by slight plastic yielding.

A statement by H. F. Moore[2] helped to confirm the investigators in setting a definite figure for ductility. He says: "When we consider ductility as an index of value of steel to be used in a structure, we must face the fact that our specifications demand an enormously greater degree of ductility than the metal would ever have to withstand in a structure, and that it seems difficult to conceive a case where a structure could withstand more than 4 or 5 per cent deformation along any dimension without failing to function." L. H. Miller, Chief Engineer of the American Institute of Steel Construction, has also stated[1] that, for towers and similar purposes for which galvanized structural steel angles are used, 5 per cent elongation about the hole should insure adequate ductility.

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[1] See Report of Subcommittee X on Embrittlement Investigation of the Society's Committee A-5 on Corrosion of Iron and Steel, *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part I, p. 211 (1931).

[2] H. F. Moore, "Test Results and Service Values of Materials," paper presented at the joint meeting of the American Society for Testing Materials and the American Institute of Mining and Metallurgical Engineers, held in New York City, February 18, 1932.

The tests made in this study have shown that the ductility about the hole in a galvanized angle is generally much higher than this, the elongation in 2 in. being frequently above 15 per cent and the percentage reduction in thickness not much lower. However, depending on various factors, among them being the thickness of the angle and the size of hole and its distance from the edge, aside from the quality of the steel itself and the workmanship in fabricating, appreciably lower values may be obtained. For this reason it would be as improper as it is unnecessary to set the limit between brittle and ductile behavior at the average ductility of commercial steel. On the other hand, it was obviously necessary to insure the detection and the definite ruling-out of embrittled material, that is, material showing in its behavior about the hole the brittleness of cast iron. Hence for the purposes of this investigation those angles are designated as injuriously embrittled which show less than 5 per cent elongation about the hole, with a corresponding lack of reduction in thickness.

It appears that material having greater ductility than this is considered by engineers as fully acceptable for tower construction. It may be emphasized again that the value of 5 per cent elongation refers to the elongation about the hole. The material of the angle itself, a fraction of an inch away from the hole, in the case of a punched hole, and up to the extreme edge of the hole in the case of a drilled hole, possesses the full ductility characteristic of structural steel, generally over 25 per cent elongation in 8 in. and over 50 per cent reduction in area.

Causes of Embrittlement:

We now come to the moot question of the embrittlement caused by galvanizing. To sum up briefly the results of this study, it has been shown, as will be described in detail further in the report, that in open-hearth structural steel angles, galvanizing itself does not have a detrimental effect, unless the holes are punched. Even with punched holes, galvanizing does not injuriously lower the ductility of open-hearth steel angles less than $\frac{3}{4}$ in. thick. However, in punched angles $\frac{3}{4}$ in. or over in thickness, galvanizing quite frequently reduces the ductility to very low values, so that a large proportion of such punched and galvanized material must be classed as brittle in respect to the behavior at the hole.

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[1] Statement made at a meeting of the Steering Committee of Subcommittee X of the Society's Committee A-5, January 7, 1932.

The Embrittlement Problem:

Although such heavy angles compose a relatively small part of the total tonnage in tower construction, they constitute, when used, the main members of the larger towers.

Embrittlement in such angles presents a decidedly disturbing problem, and not a negligible one, such as we would have if, for example, embrittlement were encountered solely in bessemer steel, as was at one time alleged. The reason this condition has not heretofore revealed itself is that little such testing has been done and because after erection of a tower the chances of its failing due to the presence of embrittled members are slight. Fortunately, a ready and not too expensive means of eliminating chances of embrittlement of heavy angles exists in drilling, sub-punching and reaming, or otherwise overcoming the effect of punching the hole. If this be done in the case of the heavy angles, the results of the study indicate that, assuming the customary use of open-hearth steel, embrittlement as an engineering problem would practically cease to exist.

A possible cause for apprehension would still remain, that is, the marked drop in ductility which has been found to occur at low temperatures, tending to corroborate old statements as to angles breaking with a brittle fracture during construction in freezing weather. It is noteworthy, however, that the results of this study have shown that also in this connection drilling or reaming the hole is highly beneficial and insures ductile behavior down to temperatures as low as −40° F. (−40° C.).

This study has been oriented to provide an engineering solution of the problem of embrittlement and not primarily to determine the ultimate causes, simple or involved as they might prove to be. In presenting the picture of the mechanism of and factors causing embrittlement, it has been necessary to stress certain ones because of their importance, the possibility of reducing or eliminating them, and because their elimination provides the most convenient solution of the problem. There can be no attempt, however, to set up any one cause over any of the others, as solely responsible for embrittlement, since all of them have been found to be inextricably interrelated and their results cumulative. For example, the susceptibility to embrittlement due to cold working, as in punching, varies in different steels; in turn the effect of pickling and galvanizing depends on the kind of steel and the severity of cold work; again the effect of the temperature of testing also depends on the foregoing; and finally all of these effects are conditioned by the size of the angle.

The discussion of these interrelated causes of embrittlement later in this report will bring out that the blame for embrittlement cannot be placed solely on either the processes of manufacturing the steel or those of fabricating and galvanizing. Though punching heavy angles has been shown to be so damaging, this does not mean that the steel-melting and making process has no hand in embrittlement, for steels do vary in their susceptibility to embrittlement in punching and galvanizing. On the other hand, in the present state of the art of steel making the fabricator and galvanizer can hardly expect the steel manufacturer to provide steel that is never susceptible to embrittlement in punched heavy angles, since it is shown that in such angles a large proportion of good quality commercial open-hearth steel is embrittled if punched, but is not embrittled when drilled or reamed.

Material Studied:

At the beginning of the study, due to the almost complete absence of failed material, a large supply of commercial structural steel angles was obtained and subjected to various tests in the as rolled, as pickled, and as galvanized conditions after punching, drilling, etc., to measure the embrittling effects of the various factors. The fabricating, pickling, and galvanizing were done in large shops according to routine commercial practice. Later the Battelle representatives spent several weeks in different steel mills examining numerous heats of steel as they were being made and rolled into structural angles. This work in the steel mills had two principal objectives, first, to collect samples which were truly representative of commercial practice, and second, to search for a heat of open-hearth steel such as had been spoken of before the inauguration of this study as especially susceptible to embrittlement, that is, ductile in the as rolled condition, but extremely brittle after pickling and galvanizing, no reference at all being made to whether it was punched or not, so that, if such material existed, it might be expected to be brittle when drilled, according to these rumors. No exceptional material of this type came to light, and no proof appeared that it exists. Finally, a large number of heats from seven steel mills were tested, in order to assure the applicability of the test methods. As a consequence, some 170 heats of commercial structural steel made in the ordinary course of manufacture, and several special materials such as Armco iron and the German Izett steel were thoroughly tested in a total of over 4000 tests and determinations. The volume of material and testing has been so great that the conclusions drawn should carry unusual weight. The conditions in the laboratory study were closely representative of engineering practice, and there should be little hesitancy in making practical application of the results.

Sponsorship:

An embrittlement research was sponsored in June, 1930, by the Utilities Research Commission of Chicago, and the results of that study have been included in writing this report. The American Society for Testing Materials instituted an additional study of the problem at Battelle Memorial Institute in December, 1930. In July, 1931, these studies were merged, and the work has since been sponsored, under the chairmanship of V. F. Hammel, by Subcommittee X of the Society's Committee A-5 on Corrosion of Iron and Steel through a Steering Committee composed as follows:

Jesse J. Shuman (Chairman), Jones & Laughlin Steel Corp.
H. O. Hill, McClintic-Marshall Corp.
W. G. Kelley, Utilities Research Commission Inc.
C. F. W. Rys, Carnegie Steel Co.
V. F. Hammel (*ex-officio*), Electric Bond and Share Co.
C. S. Trewin (*ex-officio*), New Jersey Zinc Co.

Acknowledgments:

Grateful acknowledgment is herewith made for the helpful cooperation of the committee and to the many firms who generously cooperated in providing materials and facilities for this study.

This study has been so much a joint effort that only through circumstance and for convenience has one author been named. As the nominal author, therefore, I wish to acknowledge the great debt I owe to B. N. Daniloff and G. T. Motok for their ready and efficient aid in making the great number of tests and in compiling the data, to F. Sillers, Jr., for aid in inspecting much of the steel from the mills, to M. P. Benoy and J. D. Sullivan for the chemical analyses, to W. A. Welcker, Jr., for valued aid in mechanical testing, and above all to H. W. Gillett for unfailing guidance, judgment, and encouragement, and to O. E. Harder for constant and painstaking advice and criticism and the able handling of the good-size executive task involved in the research.

II. TESTING METHODS

Angle Bend Test:

Embrittlement in galvanized structural steel angles was first noticed when angles were either accidentally or intentionally bent about a hole, and the test that was finally adopted in this study was of this nature. (For a description of the "angle bend test," see the Tentative Recommended Practice for Safeguarding Against Embrittlement of Hot-Galvanized Structural Steel Products and Procedure for Detecting Embrittlement, recommended by Subcommittee X.[1]) The sizes of holes and edge distances used in this study are given in Table IX, and special features of the test are discussed in detail

TABLE I.—STANDARD CHARPY IMPACT TESTS ON SPECIMENS FROM 6 × 6 × ½ IN. ANGLES OF DIFFERENT KINDS OF STEELS.

The tests reported here are representative of the 60 tests.

LABORATORY	CONDITION	FRACTURE IN ANGLE BEND TEST	ENERGY ABSORBED, FT-LB.[a]
		BESSEMER ANGLES	
No. 163	Rolled	Brittle	27.1
No. 164	Pickled	Brittle	29.5
No. 165	Galvanized	Brittle	23.9
		DUPLEX ANGLES	
No. 243	Rolled	Ductile	26.9
No. 244	Pickled	Ductile	30.7
No. 245	Galvanized	Brittle	30.4
No. 213	Rolled	Brittle	31.6
No. 214	Pickled	Ductile	31.7
No. 215	Galvanized	Ductile	31.1
		OPEN-HEARTH ANGLES	
No. 253	Rolled	Ductile	25.4
No. 254	Pickled	Brittle	25.7
No. 255	Galvanized	Ductile	24.4
No. 293	Rolled	Ductile	31.4
No. 294	Pickled	Ductile	30.8
No. 295	Galvanized	Ductile	31.4

[a] Average of three tests.

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[1] See *Proceedings*, Am. Soc. Testing Mats., Vol. 32, Part I, p. 614 (1932).

later in this report. Prior to this study a qualitative angle bend test had been used for inspection purposes by fabricators and users of angles, notably by C. E. Ambelang, Engineer, Electrical Transmission Design of the Public Service Company of Northern Illinois.

TABLE II.—STANDARD CHARPY IMPACT TESTS ON PICKLED, AND PICKLED AND GALVANIZED SPECIMENS, SHOWING THE EFFECT OF PICKLING TIME AND TEMPERATURE AND OF GALVANIZING.[a]

Laboratory	Kind of Steel	Size of Angle, in.	Treatment	Energy Absorbed, ft-lb.[b]
No. 98	Duplex	8 × 8 × 1	Pickled 20 minutes at 194° F. (90° C.)[c]	32
	Duplex	8 × 8 × 1	Pickled 45 minutes at 194° F. (90° C.)	30
	Duplex	8 × 8 × 1	Pickled 50 minutes at 194° F. (90° C.)	30
	Duplex	8 × 8 × 1	Pickled 20 minutes at 194° F. (90° C.) and galvanized[d]	30.5
No. 213	Duplex	6 × 6 × ½	Pickled 20 minutes at 194° F. (90° C.)	29
	Duplex	6 × 6 × ½	Pickled 45 minutes at 194° F. (90° C.)	36
	Duplex	6 × 6 × ½	Pickled 20 minutes at 194° F. (90° C.) and galvanized	30.5
No. 213	Duplex	6 × 6 × ½	As rolled	31
No. 176	Bessemer	6 × 6 × ½	Pickled 5 minutes at 140° F. (60° C.)	28
	Bessemer	6 × 6 × ½	Pickled 5 minutes at 175° F. (80° C.)	27.8
	Bessemer	6 × 6 × ½	Pickled 10 minutes at 140° F. (60° C.)	25
	Bessemer	6 × 6 × ½	Pickled 10 minutes at 175° F. (80° C.)	28.9
	Bessemer	6 × 6 × ½	Pickled 30 minutes at 140° F. (60° C.)	26.3
	Bessemer	6 × 6 × ½	Pickled 30 minutes at 175° F. (80° C.)	28
	Bessemer	6 × 6 × ½	Pickled 60 minutes at 140° F. (60° C.)	27
	Bessemer	6 × 6 × ½	Pickled 60 minutes at 175° F. (80° C.)	30.8
	Bessemer	6 × 6 × ½	Pickled 10 minutes at 140° F. (60° C.) and galvanized	26.3
No. 176	Bessemer	6 × 6 × ½	As rolled	28

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[a] The finish-machined specimens were pickled and galvanized and tested directly after pickling and galvanizing.

[b] Average of three tests.

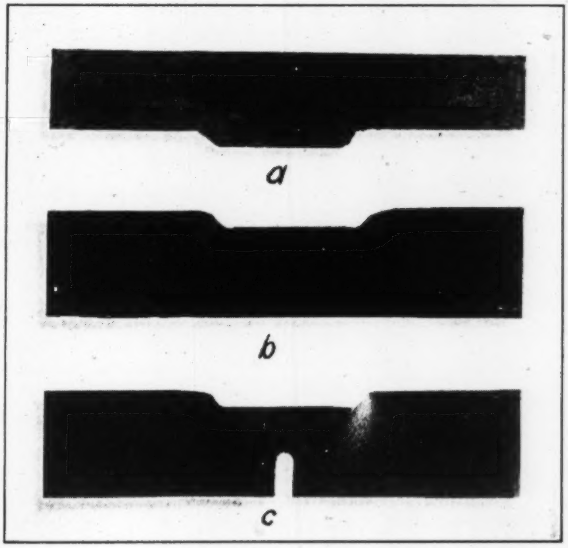
[c] Composition of pickling solution 10 per cent H_2SO_4, 12 per cent $FeSO_4$.

[d] Galvanizing temperature 840° F. (450° C.) and time three minutes.

The choice of this unusual method of test requires some explanation as well as evidence of its reliability. It should be kept in mind, however, that the more usual tests, such as tension, bend, and impact, give no indications of brittleness even in angles which in the angle bend test reveal brittleness very strikingly. Thus, specimens from punched and galvanized bessemer angles (which angles on breaking in the angle bend test would often snap so sharply as to fly out of the testing machine, and in which no measurable deformation occurred at the fracture) showed good ductility in tension, bend, and impact tests.

Non-Discriminative Character of Ordinary Notched-Bar Impact Test:

The angle bend test proved very discriminating in regard to the factors involved in embrittlement, such as the kind of steel, method of producing the hole, and pickling and galvanizing, whereas the other tests mentioned did not. Tables I and II, giving the representative results of standard Charpy impact tests[1] on bessemer, duplex, and open-hearth steel angles in the as rolled, pickled, and galvanized conditions, show very plainly that even this test,[2] which is generally



(*a*) Die. (*b*) Deeply etched compressed specimen. (*c*) Specimen, showing location of notch.

FIG. 1.—Illustration of Method of Compressing Cold Worked Impact Specimens.

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[1] The impact specimen used in these tests was the drilled, notched specimen (key-hole notch) shown on p. 444, National Metals Handbook, Am. Soc. Steel Treating (1930).

[2] It is noteworthy that invariably the workers who have studied the embrittling effects of pickling have used bend tests, not impact tests. Thus Sutton used a reversed bend test; Langdon and Grossmann found an impact test insensitive and devised a special bend test; Brenier observed that pickling a steel had no appreciable effect on impact value (Izod); H. Van de Loo used bend and twist tests.

H. Sutton, "The Influence of Pickling Operations on the Properties of Steel," *Journal*, Iron and Steel Inst., Vol. 119, p. 179 (1929).

S. C. Langdon and M. A. Grossmann, "The Embrittling Effects of Cleaning and Pickling upon Carbon Steels," *Transactions*, Am. Electrochemical Soc., Vol. 37, p. 543 (1920); Discussion, p. 576.

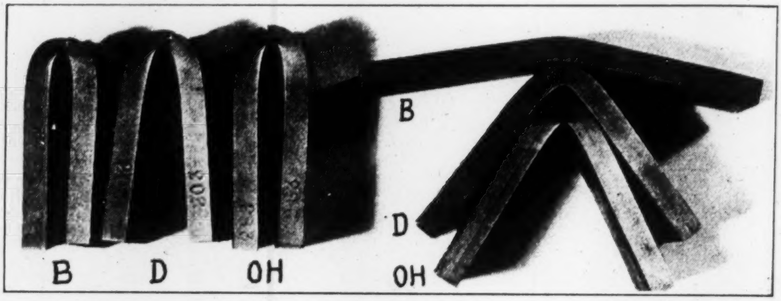
Brenier, "Effect of Pickling on Pressed Steel Elastic Washers," *Revue de Métallurgie, Memoires*, Vol. 22, p. 568 (1925).

H. Van de Loo, W. Püngel and E. H. Schulz, "The Effect of Pickling and Galvanizing on the Strength of Drawn Steel Wire," *Stahl und Eisen*, Vol. 51, p. 1585 (1931).

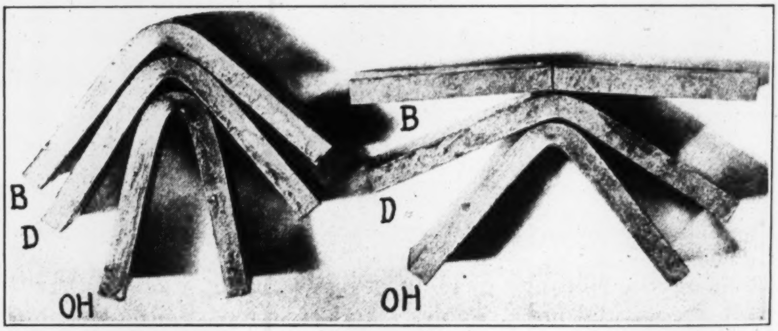
adopted for the detection of other kinds of brittleness, is insensitive to variations in the kind of embrittlement which is the subject of this study.

Cold Worked Impact Tests:

Drilled hole. Punched hole.



As rolled.



As galvanized.

FIG. 2.—Tested Hole-Bend Specimens, that is, Ordinary Bend Specimens with Punched or Drilled Holes.

B, Bessemer steel. *D*, Duplex steel. *OH*, Open-hearth steel.

NOTE.—The variations in the angle of bend in the punched and drilled, as rolled and galvanized, and bessemer, duplex, and open-hearth specimens.

The reason for the exceptional sensitivity of the angle bend test undoubtedly lies, as has been indicated, in the conditions about the hole, which after the severe cold work in punching may introduce acute notch effects. As may be seen in Fig. 12, marked differences between the three kinds of steel used were revealed when cold worked impact specimens were tried. The effects of pickling and galvanizing, however, were still not so pronounced as in some angle bend tests, apparently because the type of notch used (drilled) in the impact specimens does not happen to be so well adapted for revealing this as a punched hole.

The method of compressing the impact specimen is illustrated in Fig. 1 and is similar to that used by Bauer.[1]

Other Laboratory Tests:

After a thorough analysis of the conditions about the hole in an angle, a laboratory type of test or tests could probably be devised which would measure the susceptibility to notch propagation and brittleness in different steels after various degrees of cold working and after pickling and galvanizing. Such tests should give some indication of the suitability of a galvanized steel angle and might profitably be used for supplementary research purposes.[2] For inspection and ordinary testing, however, the angle bend test is obviously much more satisfactory.

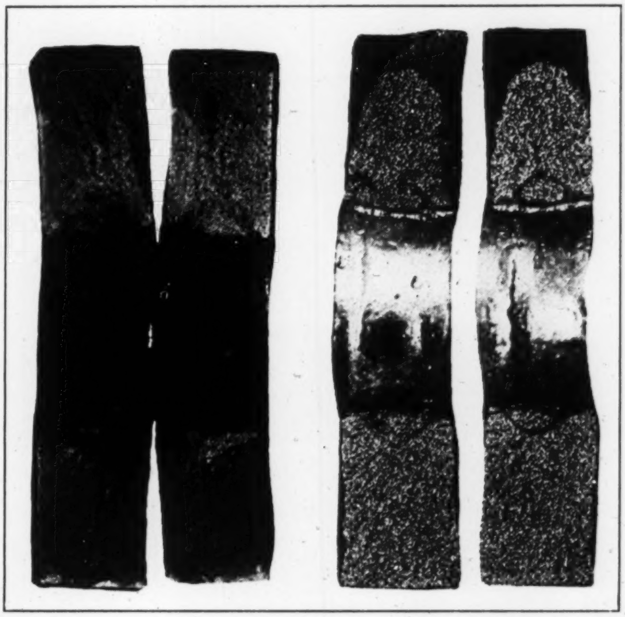


FIG. 3.—Silky and Crystalline Fractures in the Hole Tension Test.

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[1] O. Bauer, "Steel of Slight Susceptibility to Aging," *Zeitschrift*, Bayerischen Revisions-Verein, Vol. 32, p. 23 (1928).

[2] Two rather unusual types of test that might be applicable are described in the following references:

W. Kuntze, "Comparison of the Results of Different Tests, Such as Tensile, Hardness, Elongation, Contraction, Folding, Bending, Torsion, Fatigue, Notched-Bar, Etc." (Advocates the use of an extrapolated value, "Trennfestigheit," obtained by tensile tests on notched-bars, stated to indicate ability to resist flow), *First Communications*, New Internat. Assn. Testing Mats., Group D, p. 1 (1930).

G. S. von Heydekampf, "Damping Capacity of Materials," *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part II, p. 157 (1931).

Hole Bend Test:

To judge the value of a test one must consider its sensitivity and the reproducibility of the results. As will be shown further on the test appeared to be satisfactory in these respects. Moreover, two other forms of test of specimens with holes in them gave very similar results. A "hole bend test" was first tried, in which an ordinary bend specimen with a hole in the middle was given a slight preliminary bend about the hole, and then bent until fracture extended from the hole to an edge of the specimen, the angle of bend being measured. As indicated in Fig. 2, this test proved sensitive to the factors involved in embrittlement and gave results essentially similar to those of the angle bend test.

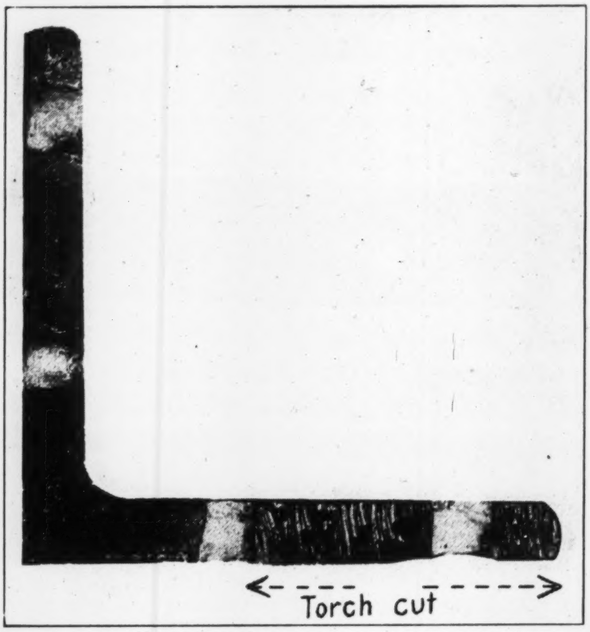
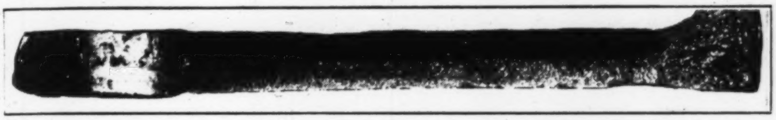


FIG. 4.—Crystalline Fracture in 8 × 8 × $\frac{15}{16}$ in. Punched Angle Which Occurred During the Erection of a Transmission Tower.

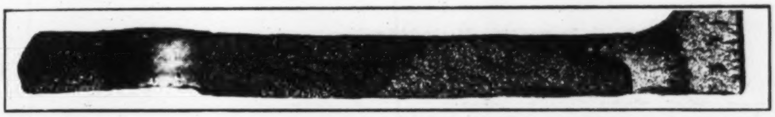
This proved to be a duplex steel angle containing 0.20 per cent carbon; 0.47 per cent manganese; 0.015 per cent phosphorous; 0.023 per cent sulfur; 0.04 per cent silicon; and 0.008 per cent nitrogen. The specimen has been torch cut on part of one leg; the remaining portions show the fracture.

Hole Tension Test:

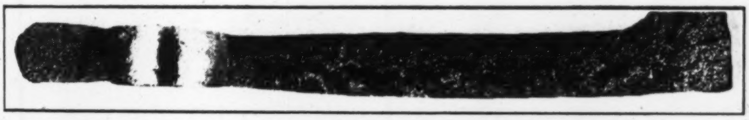
A "hole tension test," in which a longitudinal specimen with a hole in it (the width of the specimen being approximately three times the diameter of the hole) was pulled in tension, also gave closely parallel results. Typical silky and crystalline fractures of "hole tension tests" are shown in Fig. 3. This test had in its favor the fact that it might appear more familiar to the inspecting engineer because of its resemblance to the tension test. However, the specimen is more expensive to prepare, and the test does not simulate service conditions as closely as does the angle bend test.



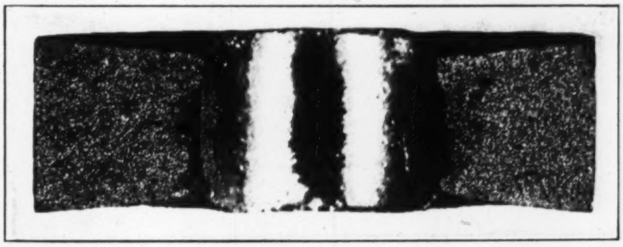
(*a*) Silky fracture in $6 \times 6 \times \frac{1}{2}$ in. angle. Note that at the right at the heel of the angle there is a crystalline area.



(*b*) Crystalline fracture in punched, galvanized, $6 \times 6 \times \frac{1}{2}$ in. bessemer angle; there was virtually no deformation at the fracture.



(*c*) Crystalline fracture in drilled, galvanized, bessemer $6 \times 6 \times \frac{1}{2}$ in. angle; although the fracture was crystalline, a good deal of deformation occurred about the hole during fracture.



(*d*) Crystalline fracture in drilled, galvanized, hole tension specimen from $8 \times 8 \times 1$ in. angle tested at −25° C. (−13° F.); though the fracture was crystalline a large amount of deformation occurred, as can be seen.

FIG. 5.—Fractures Obtained in Angle Bend and Hole Tension Tests.

Appearance of Fracture in Angle Bend Test:

Figure 4 shows the crystalline service fracture of the large punched angle which failed during erection of a transmission tower. Before this study began, the results in the angle bend test were judged primarily by the appearance of the fracture, depending upon whether it was crystalline or silky, with some attention to whether or not the angle could be heard to snap. Such merely qualitative judgment may lead to confusion, since the fractures are generally not crystalline or silky throughout, and an untrained eye may not be able to evaluate the significant differences. At best such a qualitative test depends to a large degree upon the personal element. Similar difficulties arose in the nick-bend fracture test for wrought iron.[1] That these difficulties are not merely academic is indicated by the fact that numerous retests of specimens from the only two heats of steel submitted as having been rejected for tower construction, by judging the fracture in the angle bend test, showed both to be ductile when measured quantitatively. The discrepancy might have come about because the original tests were made in cold weather, but it appears fairly probable that they were misinterpreted.

A silky fracture extending from the edge of the angle to the hole and beyond may be taken as a certain indication of good ductility. A wholly crystalline fracture, however, does not always denote low ductility. Figure 5(*c*) and (*d*) shows entirely crystalline fractures with a high degree of deformation at the fracture, as can be recognized by the marked contraction about the holes. At low testing temperatures with drilled holes it frequently occurred that a crystalline fracture formed, accompanied by considerable deformation, as shown by the elongation and the reduction in thickness. Similar behavior has been observed by others.[2]

Quantitative Angle Bent Tests and Merit Numbers:

Instead of judging by the appearance of the fracture, the method used in the study was (as described in the Tentative Recommended Practice for Safeguarding Against Embrittlement of Hot-Galvanized Structural Steel Products and Procedure for Detecting Embrittlement) to measure carefully the deformation at the fracture, and to calculate the percentage elongation about the hole along the edge of the angle, and the percentage reduction in thickness. It also seemed desirable in order to get a single value representative of the deformation at the fracture to add these two figures, so as to combine them into one "merit number" representing ductility. By introducing these quantitative measurements the test has been made fairly precise and provides a very satisfactory inspection method.

From the research standpoint of evaluating the various factors in embrittlement the quantitative data provided by the test were, of course, essential.

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[1] H. S. Rawdon and S. Epstein, "The Nick-Bend Test for Wrought Iron," U. S. Bureau of Standards *Technologic Paper No. 252*, Vol. 18, p. 115 (1924).

[2] H. J. Gough and A. J. Murphy, "The Effect of Low Temperature on the Shock-Resisting Properties of New Wrought-Iron Chains," *Proceedings*, Inst. Mechanical Engrs., No. 5, p. 1159 (1930).

Rate of Loading—Angle Drop Tests:

The rate of loading in the angle bend test does not greatly influence the results. It was suggested early in the study that the application of an impact blow instead of a bending load, would more nearly simulate conditions which the angles might happen to be subjected to in service. "Angle drop" tests were accordingly made in which the blow was applied with a large steam hammer. These tests showed that the impact blow did not decrease the amount of deformation at the fracture but instead, generally increased it considerably, as may be seen from representative data shown in Table III.

TABLE III.—COMPARISON OF RESULTS ON PUNCHED GALVANIZED 6 × 6 × $\frac{1}{2}$ IN. ANGLES IN ANGLE BEND AND ANGLE DROP TEST.

The values are representative of some 65 tests.

Laboratory	Kind of Test	Kind of Steel	Testing Temperature		Elongation in 2 in., per cent	Reduction in Thickness, per cent	Merit Number
			deg. Fahr.	deg. Cent.			
No. 151...	Angle drop..........	Bessemer............	77	25	0.6	0.9	1.5
No. 148...	Angle bend..........	Bessemer............	77	25	0.6	0.9	1.5
No. 212...	Angle drop..........	Duplex.............	77	25	14	15.7	29.7
No. 215...	Angle bend..........	Duplex.............	77	25	9.5	11	20.5
No. 261...	Angle drop..........	Open hearth.........	77	25	22	21.9	43.9
No. 265...	Angle bend..........	Open hearth.........	77	25	12	12.6	24.6
No. 432...	Angle drop..........	Duplex.............	−13	−25	8	11.8	19.8
No. 428...	Angle bend..........	Duplex.............	−13	−25	0.5	0.8	1.3
No. 462...	Angle drop..........	Open hearth.........	−13	−25	9	8.9	17.9
No. 458...	Angle bend..........	Open hearth.........	−13	−25	15	6.9	21.9

Accuracy of Measurements:

A considerable number of elongation and reduction measurements on angle bend test specimens were checked at the Institute by three rather inexperienced observers to get a line on the observational errors that might be expected. The results showed that the amount of such errors should not be more than 5 per cent of the elongation value and 10 per cent of the reduction of thickness value.

Presentation of Data:

The mass of data obtained in the study was so great that on several of the points brought out in tabular form, space is lacking to include all the data; so for the sake of brevity, representative values are cited. In numerous instances supporting data have been omitted entirely and the statement merely made that such evidence was obtained. The omitted data have been tabulated and filed, however, and can be supplied to those who wish to obtain them.

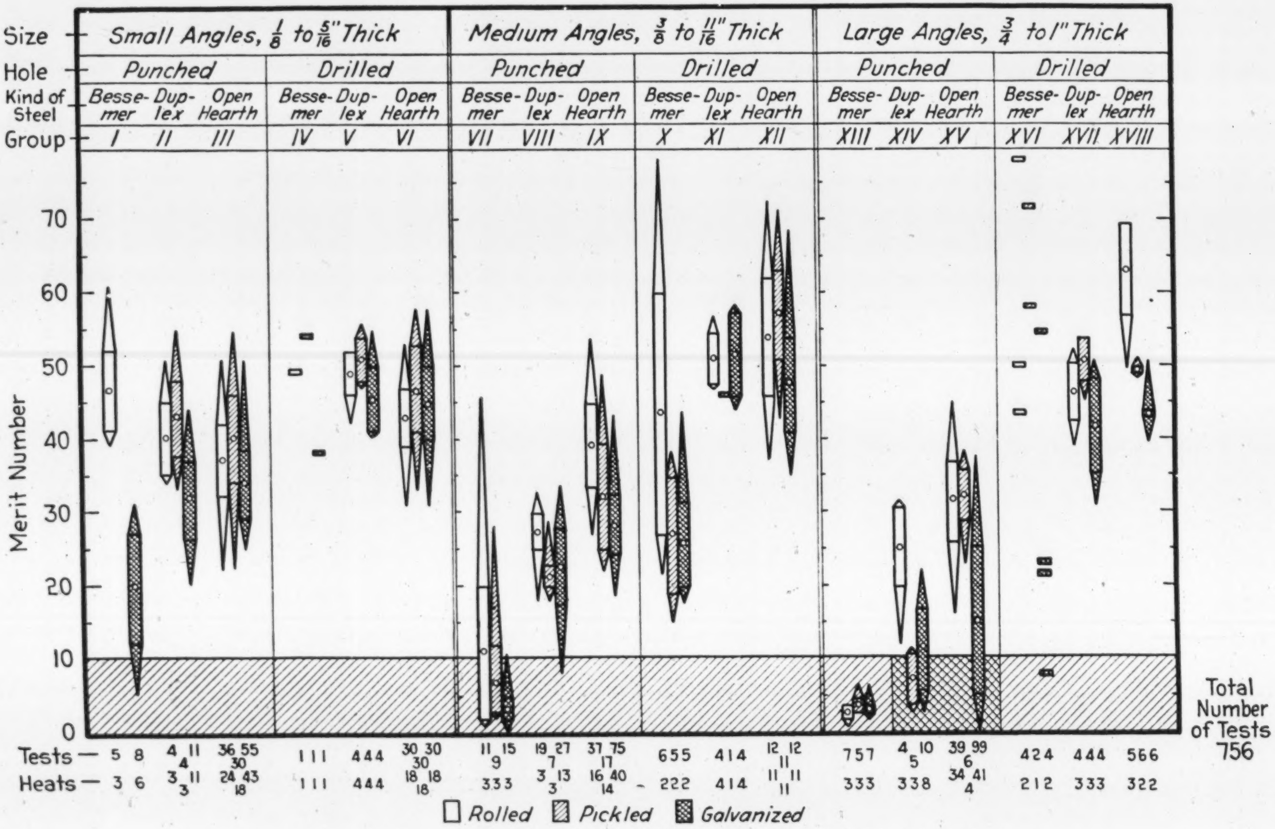

FIG. 6.—Summarized Results of Angle Bend Tests at 25° C. (77° F.).

NOTE.—If the elongation on the small and medium size angles had been calculated on a 1-in. gage length the merit numbers would have been increased about 50 and 30 per cent, respectively.

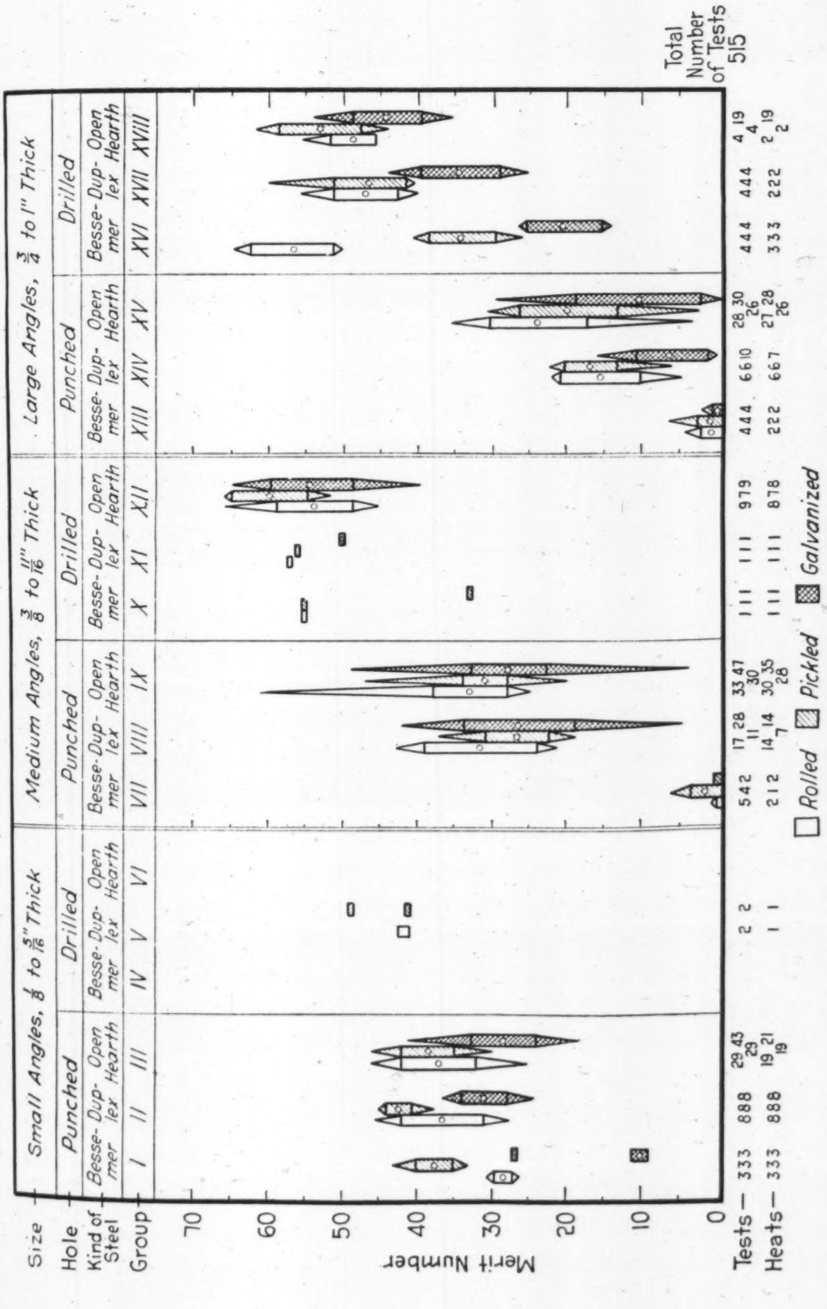

FIG. 7.—Summarized Results of Hole Tension Tests at 25° C. (77° F.).

III. RESULTS

The main results of the present study may be gathered from Figs. 6 to 8, in which the bulk of the angle bend and hole tension tests have been plotted according to the merit numbers obtained, that is, according to the sum of the percentage elongation in 2 in.[1] and the percentage reduction in thickness. The angles have been divided into three groups with reference to size, as follows: Small $\frac{1}{8}$ to $\frac{5}{16}$ in. in thickness; medium $\frac{3}{8}$ to $\frac{11}{16}$ in. in thickness; and large $\frac{3}{4}$ to 1 in. in thickness. It should be emphasized that the use of a 1-in. gage length in determining the percentage elongation and the merit number for the small and medium size angles reported in Fig. 6 would have materially increased these values, as is shown later in Table XIII.

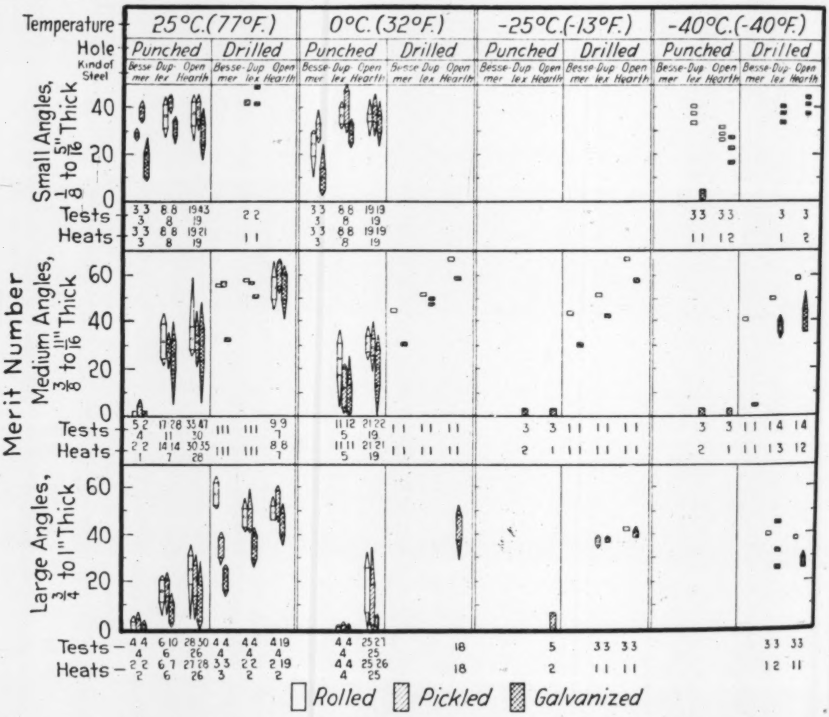

FIG. 8.—Summarized Results of Hole Tension Tests Showing the Effect of Lowered Testing Temperature.

The data have been arranged to bring out the effects of the various factors in embrittlement, which can be read off from Figs. 6 and 7 as follows: size of angle, kind of hole, kind of steel, and whether the steel was as rolled, pickled, or galvanized. In Fig. 8 the effect of the temperature of testing is also shown.

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[1] See p. 326 for comment on the gage length for various sizes of angles.

Partly due to the large number of tests made from many heats of steel and to the grouping of the angles into three rather broad divisions according to size, the values showed considerable spread, and it has seemed advisable to indicate this by representing the results not as single points showing averages, but as rectangular figures tapering off at both ends to the maximum and minimum values obtained. The upper horizontal of the rectangle indicates the average of the upper half of the values, and the lower horizontal the average of the lower half. The value for the average of all of the tests is represented by the circle midway between the two horizontal lines. Where too few tests were made to justify representing them by a continuous rectangular area each value has been shown separately.

"Injurious Embrittlement":

In Fig. 6 depicting results of 756 angle bend tests made at 25° C. (77° F.) a horizontal line has been drawn across the figure at the merit number 10 and the area beneath the line shaded. Values in this shaded area represent brittle behavior according to the Proposed Tentative Recommended Practice for Safeguarding Against Embrittlement of Hot-Galvanized Structural Steel Products and Procedure for Detecting Embrittlement, recommended by Subcommittee X. By the term "injurious embrittlement" in this report is meant a lowering of the merit number to below 10.

Large Angles—Punched versus Drilled Holes:

If we consider only commercial structural steel angles, which excludes bessemer steel, it can be seen in Fig. 6 that the only series of test values which dip to a considerable extent into the shaded area are in Groups XIV and XV (which have been cross-hatched in the shaded area) indicating plainly that serious embrittlement after galvanizing was only encountered in the large punched angles. The figure brings out strikingly that in these large angles of commercial structural steel the use of drilled[1] instead of punched holes resulted in extremely high values after galvanizing—three and four times above the limiting merit number of 10 as shown in Groups XVII and XVIII. In what proportion and to what extent the large punched galvanized angles were embrittled will be shown in further detail below. The fact that these angles $\frac{3}{4}$ to 1 in. thick were embrittled, and these only, and that embrittlement was avoided by drilling (or otherwise overcoming the injurious effect of punching the hole) is undoubtedly the outstanding point in the study.

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[1] In the discussions of this report the words "drilling" and "drilled" are to be taken to include sub-punching and reaming as equivalent to drilling.

Small and Medium Size Angles:

In the small size angles it can be seen in Fig. 6 that the values for both duplex and open-hearth steel were well above the shaded area; not a single small size commercial angle was injuriously embrittled after punching and galvanizing. This was true in the main also for the medium size angles. After punching and galvanizing, out of 27 tests of medium size angles from 13 heats of duplex steel, only two tests fell slightly below a merit number of 10 into the shaded area; out of 75 tests of angles from 40 heats of open-hearth steel not a single one fell into the shaded area, the lowest merit number being 18 and the average of the *lower* half of the values being 24. Thus injurious embrittlement was not found in the great number of tests made of punched and galvanized medium size open-hearth angles, and was found to be extremely rare in similar duplex steel angles (in a lesser number of tests of fewer heats).

Bessemer Steel:

Bessemer steel in small size angles after punching and galvanizing generally gave a merit number over 10, but with some values below this limit. These values will be increased about 50 per cent when the elongation is calculated on a 1-in. gage length, as will be discussed later. In the medium size punched angles bessemer steel gave a large proportion of brittle tests even in the as rolled condition; after galvanizing virtually all of the samples proved brittle. The large size punched bessemer angles were brittle both as rolled and after galvanizing. The only drilled angle which gave a merit number below 10 was a galvanized bessemer angle indicating this steel to be inherently brittle or susceptible to injurious embrittlement in galvanizing, even in the absence of the deleterious effect of punching. However, the data indicate that it would be preferable to use a large drilled bessemer angle rather than a large punched open-hearth angle, this statement, of course, being made merely for emphasis and not because of any contemplated use of large bessemer angles.

Effect of Pickling:

The embrittling effect of pickling, as can be seen in Fig. 6, was small, although occasionally in bessemer steel, as in the medium size drilled bessemer angles, or after severe punching, as in the large punched duplex angles, appreciable lowering in the ductility resulted, sufficient in the latter case to produce injurious embrittlement.

Effect of Galvanizing:

In commercial structural steel the embrittling effect of galvanizing was negligible, except after severe punching as in the heavy angles. Thus in the small drilled and even punched angles galvanizing had little effect in reducing the merit numbers. In the medium size *punched* angles the effect of galvanizing was appreciable, although not enough to produce injurious embrittlement, whereas in the medium size *drilled* angles the effect of galvanizing was very small. The effect of galvanizing was negligible in the large drilled angles but was pronounced in the large punched angles, the effect of galvanizing being such as to result in injurious embrittlement. It may be considered that although punching may leave the large angles still ductile, it frequently brings them near to the verge of brittleness, so that the added effect of galvanizing (magnified because of the severe cold work) is sufficient to produce injurious embrittlement.

Susceptibility to Embrittlement:

The susceptibility to embrittlement in galvanizing (punching, pickling and galvanizing) may be judged by comparing the values for the drilled, as rolled specimens with those for the punched galvanized specimens in Fig. 6. According to this bessemer steel had the greatest susceptibility to embrittlement. This is well illustrated by the medium size angles where the average merit number for the drilled specimens is above 40, while for the punched and galvanized specimens it is below 4. The small and medium size duplex angles had a slightly greater susceptibility to embrittlement than the corresponding open-hearth angles, whereas this relation was reversed with respect to the large size angles.

Reliability of Angle Bend Test:

Turning now to Fig. 7 which shows the results of the hole tension tests, and comparing it with Fig. 6 of the angle bend tests, the striking parallelism between the results in the two types of test is clearly brought out. The hole tension test proved somewhat more severe than the angle bend test. This was probably due in part to the more nearly axial loading conditions in the hole tension test which permitted fracture to start more readily from the hole outward and tended to reduce the ductility. Moreover, the hole tension specimens were cut from the middle of the leg of the angle; here, particularly if any segregation existed, somewhat lower ductility would be expected than near the rolled edge of the angle where fracture starts in the angle bend test. The very similar results obtained in

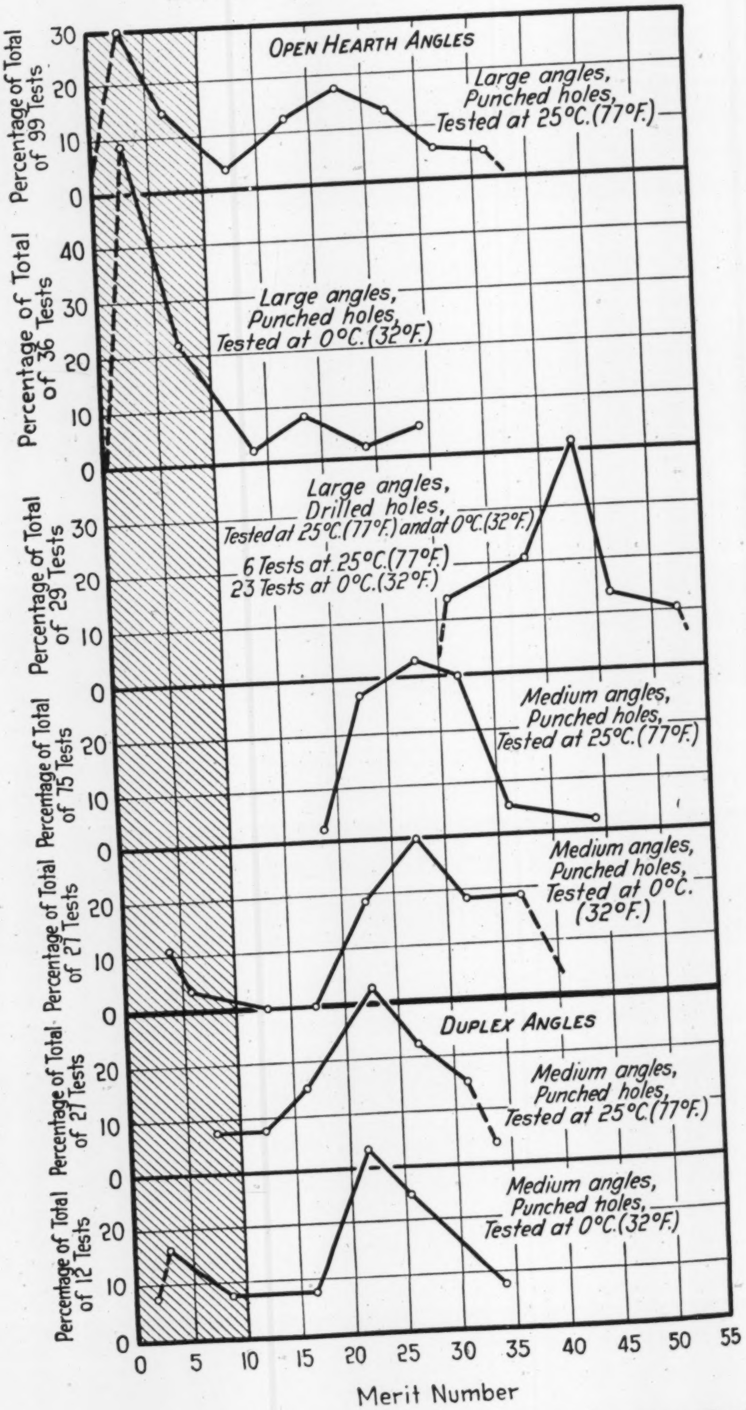

FIG. 9.—Frequency Curves of Angle Bend Tests of Galvanized Open Hearth and Duplex Angles.

The areas below a merit number of 10 have been shaded.

the two types of test should confirm the conclusions that may be drawn from either one. They further constitute strong evidence that the tests are reliable and actually indicative of the conditions it is desired to study, and that the results are not merely governed by accidental, unknown, or irrelevant factors having their origin in the unusual test procedure, as has been claimed by some in respect to angle bend tests prior to the development of the quantitative procedure. The hole tension test appears to be well adapted for research on material other than structural shapes.

Lowered Testing Temperature:

Lowering the temperature of testing had a decided embrittling effect in punched, but not in drilled, galvanized commercial structural steel angles, as shown in Fig. 8, giving the results of hole tension tests made at room temperature and at lower temperatures down to -40° C. (−40° F.). It is noteworthy that lowering the testing temperature only 25° C. (77° F.), that is to 0° C. (32° F.), caused decidedly more brittle behavior in medium and large size angles. The effect of lowering the testing temperature to 0° C. (32° F.) on punched and galvanized medium size and large open-hearth angles in the angle bend test is shown by the frequency curves in Fig. 9, which indicate that in the medium size angles a drop in temperature to 0° C. (32° F.) caused some injurious embrittlement. Since this is not unusually cold, the adverse effect of lowered temperature should be remembered during fabrication and erection of towers, and the testing temperature must be controlled in making the angle bend test, as is required in the Proposed Tentative Recommended Practice for Safeguarding Against Embrittlement of Hot-Galvanized Structural Steel Products and Procedure for Detecting Embrittlement, recommended by Subcommittee X. It appears from Fig. 8 that the adverse effect of lowered temperature was somewhat more pronounced in duplex than in open-hearth steel. Figure 9 also shows frequency curves of medium size punched and galvanized duplex angles tested at 25° C. (77° F.) and 0° C. (32° F.) in the angle bend test. Comparing the duplex and open-hearth angles in Fig. 9 it can be seen that at 0° C. (32° F.) a slightly greater proportion of duplex steel angles showed injurious embrittlement than similar open-hearth steel angles. Upon lowering the temperature of testing still further to −25° C. (−13° F.) completely brittle behavior resulted in the medium and large size punched angles, although the small punched open-hearth angles still remained ductile at −40° C. (−40° F.). The outstanding point of the tests at this low temperature was that both the medium size and large galvanized commercial structural steel angles with drilled holes showed high ductility, indicating the great value of drilling as a recourse in overcoming embrittlement produced by low temperature. The results similar to the above obtained in angle bend tests at 0 and −25° C. (32 and −13° F.) are summarized in Fig. 10.

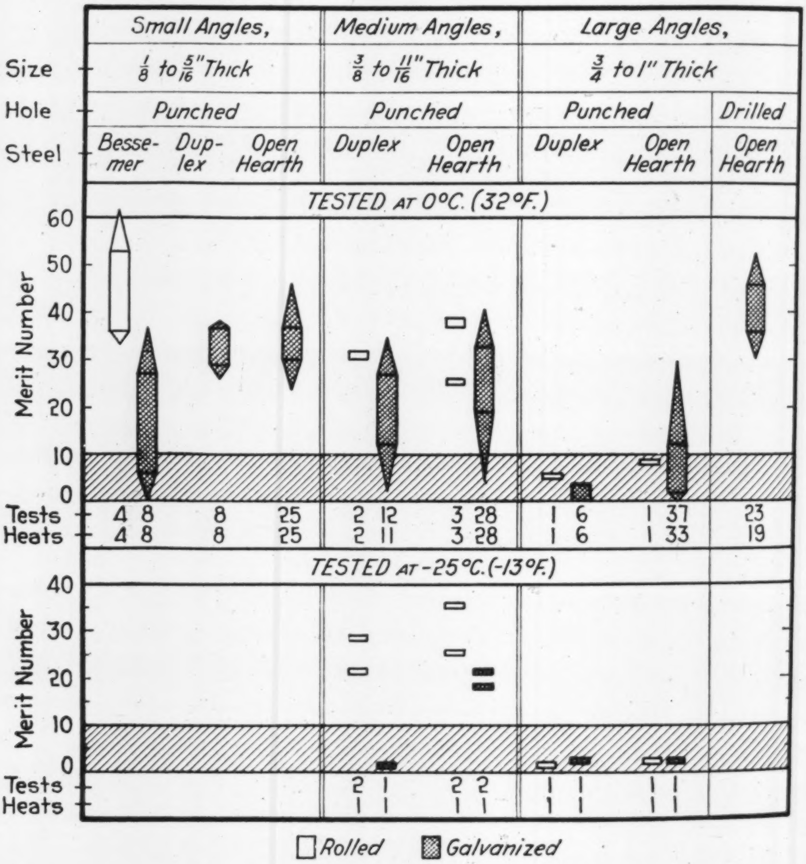

FIG. 10.—Summarized Results of Angle Bend Tests at 0° and −25° C. (32 and −13° F.).

Extent of Embrittlement in Large Angles—Scatter:

As has already been pointed out virtually the entire problem of galvanizing embrittlement resides in the frequent occurrence of brittleness in the large punched and galvanized open-hearth angles. The seriousness of the case may be further gaged from Table IV, summarizing the angle bend test data on such angles tested at 25° C.

(75° F.). In the 6-in. angles $\frac{3}{4}$ to 1 in. thick, 24 out of 49 tests, or 49 per cent, showed brittle behavior, and in the 8-in. angles 19 out of 49 tests, or 39 per cent, showed serious embrittlement. In the 6-in. angles 14 out of the 21 heats tested, or 66 per cent, contained specimens with a merit number under 10, and in the 8-in. angles 7 out of the 19 heats tested, or 37 per cent, showed an equally low merit number. Expressing it in still another way, it transpired that out of 40 heats of commercial open-hearth and duplex steel received from 8 sources, the steel from not a single source was entirely free from injurious embrittlement in galvanized angles $\frac{3}{4}$ to 1 in. thick carrying punched holes. Turning to the results on the heavy angles plotted in Fig. 9 in the form of frequency curves, the scatter in results and the large proportion of low values in the punched angles (with an even greater proportion at 0° C. (32° F.)) is in striking contrast to the high and very uniform values obtained with the drilled holes at both 25 and 0° C. (77 and 32° F.).

TABLE IV.—SUMMARY OF ANGLE BEND TESTS OF LARGE PUNCHED GALVANIZED COMMERCIAL STRUCTURAL STEEL ANGLES.

The values for the 6-in. angles averaged lower than those for the 8-in. angles, apparently because of the lesser edge distance in the former.

Size of Angle, in.	Size of Hole, in.	Edge Distance, in.	Number of Tests	Number of Heats	Merit Number				Samples with Merit Number Under 10		Heats Containing Samples with Merit Number Under 10	
					Minimum	Average of Lower Half of Values	Average of Upper Half of Values	Maximum	Number of Samples	Percentage	Number of Heats	Percentage
$6 \times 3\frac{1}{2} \times \frac{3}{4}$	$\frac{15}{16}$	$1\frac{1}{4}$	1	1	4	....	....	....	1	100	1	100
$6 \times 6 \times \frac{3}{4}$	$\frac{15}{16}$	$1\frac{1}{4}$	30	13	2.1	7.4	25.4	35.5	12	40	7	53.8
$6 \times 4 \times \frac{3}{4}$	$\frac{15}{16}$	$1\frac{1}{4}$	4	4	0	2	13	19	3	75	3	75
$6 \times 6 \times \frac{7}{8}$	$\frac{15}{16}$	$1\frac{1}{4}$	4	1	5.2	14.2	22	23.3	1	25	1	100
$6 \times 4 \times \frac{7}{8}$	$\frac{15}{16}$	$1\frac{1}{4}$	6	1	2	3.2	13.1	15.1	3	50	1	100
$6 \times 6 \times 1$	$\frac{15}{16}$	$1\frac{1}{4}$	4	1	0.8	0.9	2.7	2.9	4	100	1	100
$8 \times 3\frac{1}{2} \times \frac{3}{4}$	$1\frac{3}{16}$	$1\frac{5}{8}$	4	1	17	18.7	24.8	25.4	0	0	0	0
$8 \times 6 \times \frac{3}{4}$	$1\frac{3}{16}$	$1\frac{5}{8}$	1	1	35.5	....	....	....	0	0	0	0
$8 \times 8 \times \frac{3}{4}$	$1\frac{3}{16}$	$1\frac{5}{8}$	10	5	2	16.5	25.4	30.8	1	10	1	20
$8 \times 8 \times \frac{7}{8}$	$1\frac{3}{16}$	$1\frac{5}{8}$	18	6	1.4	4.8	16.3	29	12	66	4	66
$8 \times 8 \times \frac{15}{16}$	$1\frac{3}{16}$	$1\frac{5}{8}$	1	1	21	....	....	....	0	0	0	0
$8 \times 8 \times 1$	$1\frac{3}{16}$	$1\frac{5}{8}$	11	4	4	20	34.4	38	2	18	1	25
$8 \times 6 \times 1$	$1\frac{3}{16}$	$1\frac{5}{8}$	4	1	0	0	1	2	4	100	1	100
TOTALS FOR 6- AND 8-IN. ANGLES												
6	$\frac{15}{16}$	$1\frac{1}{4}$	49	21	0	3.7	22.3	35.5	24	49	14	66
8	$1\frac{3}{16}$	$1\frac{5}{8}$	49	19	0	7.2	24.4	38	19	39	7	36.8

In the large punched and galvanized angles the scatter in results was extreme, ductile and brittle tests being obtained from the same lengths of angles, as for example, in the punched angles of Table V. (In similar tests of angles from 20 heats of steel, 7 of the 20 gave the maximum scatter obtainable for the number of tests made.) On the other hand the drilled specimens in Table V which were alternated with the punched specimens in the same length of angle gave very uniform results. The uniformity of results in the drilled tests, as contrasted with the scatter in the punched tests in Fig. 9, has already been mentioned. Note in Fig. 9 that the medium size punched angles also gave uniform results; that is, they were all ductile.

TABLE V.—CHECK ANGLE BEND TESTS OF GALVANIZED SPECIMENS FROM A LENGTH OF AN $8 \times 8 \times \frac{7}{8}$ IN. OPEN-HEARTH ANGLE TO DETERMINE "SCATTER."

The values have been chosen as representative of 20 tests.

Laboratory	Kind of Hole	Maximum Load, lb.	Elongation in 2 in., per cent	Reduction in Thickness, per cent	Merit Number	Fracture	
						Between Hole and Edge	Between Hole and Heel
No. S-11...	Punched..........	101 900	3	2.2	5.2	Crystalline	Crystalline
No. S-13...	Punched..........	109 100	12.5	3.7	16.2	45 deg. silky	Crystalline
No. S-15...	Punched..........	115 500	17.5	3.7	21.2	45 deg. silky	Crystalline
No. S-17...	Punched..........	100 000	1	1.5	2.5	Crystalline	Crystalline
No. S-19...	Punched..........	99 500	0	1.4	1.4	Crystalline	Crystalline
No. S-12...	Drilled............	135 000	27.5	18.1	45.6	45 deg. silky	45 deg. silky
No. S-14...	Drilled............	138 600	32.5	18.1	50.6	45 deg. silky	Crystalline
No. S-16...	Drilled............	135 200	25	18.6	43.6	45 deg. silky	45 deg. silky
No. S-18...	Drilled............	137 900	27.5	17.7	45.2	45 deg. silky	45 deg. silky
No. S-20...	Drilled............	133 600	25	14.7	39.7	45 deg. silky	45 deg. silky

The above seems to be conclusive evidence that the scatter in the large punched angles is not due to any fault in the method of testing; on the contrary the test obviously gives a faithful reproduction of what may be expected in practice. Punching the large angles apparently puts them in a borderline condition, where they may behave either in a ductile or brittle manner, depending on small chance variations. Scatter in results is a characteristic of such borderline conditions in tests of notched material.[1]

Procedure in Punching, Pickling and Galvanizing:

In preparing the angles for testing, commercial fabricating and galvanizing practice was followed; the average procedure in pickling and galvanizing is given in Table VI. For the pickled condition the angles were tested the same day or the day after pickling. No inhibitor was used in the pickling solution. After pickling the samples were rinsed in water, and after galvanizing they were cooled in water, the latter practice having been found to be without effect on embrittlement.[1] The angles were punched according to ordinary shop practice.

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[1] R. H. Greaves and J. A. Jones, "The Effect of Temperature on the Behavior of Iron and Steel in the Notched-Bar Impact Test," *Journal*, Iron and Steel Inst., Vol. 112, p. 123 (1925).

F. Fettweiss, Kerbzähigkeit, Section D 1, pp. 1–6 of Werkstoff-Handbuch (Stahl und Eisen) by K. Daeves, Verlag Stahleisen, m.b.H. (1928).

TABLE VI.—PROCEDURE FOLLOWED IN PICKLING AND GALVANIZING.

PICKLING	
Solution	10 per cent sulfuric acid 12 per cent ferrous sulfate
Time in bath	small and medium size angles, 25 minutes large angles, 45 minutes
Temperature of bath	170° F. (75° C.)
Time between pickling and galvanizing	10 minutes
GALVANIZING	
Temperature of zinc bath	860° F. (460° C.)
Time in bath	small and medium size angles, 3 minutes large angles, 4 minutes

TABLE VII.—EFFECT OF CLEARANCE BETWEEN PUNCH AND DIE IN ANGLE BEND TEST OF PUNCHED ANGLES.

$6 \times 6 \times \frac{1}{2}$ in. duplex angles used in these tests.

LABORATORY	CLEARANCE, IN.	MAXIMUM LOAD, LB.	MERIT NUMBER
	AS ROLLED		
No. 437	$\frac{1}{32}$	60 500	30.3
No. 433	$\frac{1}{16}$	59 900	28.3
No. 438	$\frac{3}{32}$	61 000	29.2
	GALVANIZED		
No. 439	$\frac{1}{32}$	58 200	26
No. 434	$\frac{1}{16}$	59 800	23.7
No. 440	$\frac{3}{32}$	58 800	23.9

TABLE VIII.—EFFECT OF USING NEW (SHARP) AND OLD (DULL) PUNCH IN ANGLE BEND TESTS.

Tests on $6 \times 6 \times \frac{1}{2}$ in. angles.

LABORATORY	KIND OF STEEL	PUNCH	MAXIMUM LOAD, LB.	MERIT NUMBER
		AS ROLLED		
No. 441	Duplex	New	60 200	32.5
No. 443	Duplex	Old	61 000	29.7
No. 463	Open hearth	New	58 400	40.7
No. 465	Open hearth	Old	56 900	38.3
		GALVANIZED		
No. 442	Duplex	New	62 200	26.3
No. 444	Duplex	Old	60 000	23.1
No. 464	Open hearth	New	53 900	28.9
No. 466	Open hearth	Old	53 600	32.1

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[1] V. F. Hammel, *et al.*, Report of Technical Committee III on Specifications for Zinc Coating on Structural Steel Shapes, Plates, and Bars and Their Products, *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part I, p. 244 (1930).

It had been suggested that the clearance between punch and die and the condition of these tools would materially influence the amount of damage done in punching, but the test results in Tables VII and VIII indicate that even considerable variation in these factors produced no very marked effect.

Size and Location of Hole:

With regard to the important matter of the size and location of the hole, it was evident that to standardize these test conditions for use in this study, some definite set of values would have to be established. The minimum edge distances and largest holes permitted in one of the building codes[1] were chosen, since no uniformly accepted code for tower practice has been published. Table IX shows the sizes of holes, edge distances, and "edge material" used in the study and the corresponding values, somewhat more severe (as is evident from the discussion which follows), used by two companies in transmission tower construction. For the hole tension tests the same size hole and edge distance were used as for the angle bend tests, the width of the specimen being twice the edge distance.

TABLE IX.—DIAMETER OF HOLE AND EDGE DISTANCE.

Larger Leg of Angle, in.	Values Used in Study			Values Used in Transmission Towers					
				Company A			Company B		
	Diameter of Hole, in.	Edge Distance,[a] in.	Edge Material,[b] in.	Diameter of Hole, in.	Edge Distance,[a] in.	Edge Material,[b] in.	Diameter of Hole, in.	Edge Distance,[a] in.	Edge Material,[b] in.
$1\frac{1}{2}$	...	...	...	$\frac{9}{16}$	$\frac{9}{16}$	$\frac{9}{32}$	$\frac{9}{16}$	$\frac{9}{16}$	$\frac{9}{32}$
$1\frac{3}{4}$	$\frac{9}{16}$	$\frac{7}{8}$	$\frac{19}{32}$	$\frac{11}{16}$	$\frac{11}{16}$	$\frac{11}{32}$	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{13}{32}$
2	$\frac{11}{16}$	1	$\frac{21}{32}$	$\frac{11}{16}$	$\frac{11}{16}$	$\frac{11}{32}$	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{13}{32}$
$2\frac{1}{4}$	$\frac{13}{16}$	$1\frac{1}{8}$	$\frac{23}{32}$	$\frac{11}{16}$	$\frac{11}{16}$	$\frac{11}{32}$	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{13}{32}$
$2\frac{1}{2}$	$\frac{13}{16}$	$1\frac{1}{8}$	$\frac{23}{32}$	$\frac{11}{16}$	$\frac{11}{16}$	$\frac{11}{32}$	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{13}{32}$
3	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{13}{32}$	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{13}{32}$
$3\frac{1}{2}$	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	$\frac{13}{16}$	$\frac{7}{8}$	$\frac{15}{32}$	$\frac{13}{16}$	1	$\frac{19}{32}$
4	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	$\frac{13}{16}$	$\frac{7}{8}$	$\frac{15}{32}$	$\frac{13}{16}$	1	$\frac{19}{32}$
$4\frac{1}{2}$	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	...	...	...	$\frac{13}{16}$	1	$\frac{19}{32}$
5	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	$\frac{13}{16}$	1	$\frac{19}{32}$	$\frac{13}{16}$	1	$\frac{19}{32}$
6[c]	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	$\frac{13}{16}$	1	$\frac{19}{32}$	$\frac{13}{16}$	1	$\frac{19}{32}$
6[d]	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$
7	$1\frac{1}{16}$	$1\frac{3}{8}$	$\frac{27}{32}$	...	...	...	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$
8	$1\frac{3}{16}$	$1\frac{5}{8}$	$\frac{33}{32}$	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$

[a] Distance from center of hole to edge of angle.
[b] Distance from outer edge of hole to edge of angle.
[c] Up to $\frac{3}{4}$ in. thick.
[d] $\frac{3}{4}$ in. and thicker.

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[1] Bethlehem Steel Co., "Standard Structural Shapes, Shipbuilding and Car Building Shapes," p. 312 (1929).

Since it was necessary to determine the relationship between the results obtained when using the different sets of values in Table IX, a series of such comparison angle bend tests was made. Before going into these results, it will be instructive to examine the data in Tables X and XI. These data indicate that in both angle bend and hole tension tests the main variable in this respect is the "edge material"; that is, the merit number obtained varies mainly with the amount of metal which undergoes deformation between the outer edge of

TABLE X.—EFFECT OF VARYING DIAMETER OF HOLE AND EDGE DISTANCE[a] IN ANGLE BEND TESTS OF PUNCHED GALVANIZED OPEN-HEARTH $6 \times 6 \times \frac{1}{2}$ IN. ANGLES.

The values are representative of 18 tests.

Laboratory	Diameter of Hole, in.	Edge Distance,[a] in.	Edge Material,[b] in.	Maximum Load, lb.	Elongation in 2 in., per cent	Reduction in Thickness, per cent	Merit Number
No. 452.........	$\frac{13}{16}$	$2\frac{5}{32}$	$1\frac{3}{4}$	66 450	37.5	19.8	57.3
No. 454.........	$\frac{13}{16}$	$1\frac{21}{32}$	$1\frac{1}{4}$	62 500	26	18.2	44.2
No. 478.........	$\frac{13}{16}$	$1\frac{5}{32}$	$\frac{3}{4}$	54 900	14.5	15.8	30.3
No. 480.........	$1\frac{1}{4}$	$1\frac{3}{8}$	$\frac{3}{4}$	50 300	14.5	14	28.5
No. 479.........	$1\frac{1}{16}$	$1\frac{9}{32}$	$\frac{3}{4}$	53 200	14.5	19.2	33.7
No. 477.........	$\frac{9}{16}$	$1\frac{1}{32}$	$\frac{3}{4}$	59 800	18	13.7	31.7

[a] Distance from center of hole to edge of angle.
[b] Distance from outer edge of hole to edge of angle.

TABLE XI.—EFFECT OF VARYING DIAMETER OF HOLE AND EDGE DISTANCE IN HOLE TENSION TEST OF PUNCHED AND GALVANIZED OPEN-HEARTH ANGLES.

The values are representative of 40 tests.

Laboratory	Size of Angle, in.	Diameter of Hole, in.	Edge Distance, in.	Edge Material, in.	Maximum Load, lb.	Elongation in 2 in., per cent	Reduction in Thickness, per cent	Merit Number
No. 32M-33......	$6 \times 6 \times \frac{1}{2}$	$\frac{15}{16}$	$1\frac{1}{2}$	$\frac{33}{32}$	55 700	15	19	34
No. 32M-3.......	$6 \times 6 \times \frac{1}{2}$	$\frac{13}{16}$	$1\frac{1}{4}$	$\frac{27}{32}$	41 100	12	17	29
No 32M-5.......	$6 \times 6 \times \frac{1}{2}$	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	42 900	15	12	27
No. 32M-35......	$6 \times 6 \times \frac{1}{2}$	$\frac{17}{16}$	$1\frac{1}{4}$	$\frac{23}{32}$	37 600	13	13	26
No. 32M-1.......	$6 \times 6 \times \frac{1}{2}$	$\frac{15}{16}$	1	$\frac{17}{32}$	27 500	11	11	22
No. 32M-21......	$4 \times 4 \times \frac{3}{8}$	$\frac{15}{16}$	$1\frac{1}{2}$	$\frac{33}{32}$	32 700	18	18	36
No. 32M-13......	$4 \times 4 \times \frac{3}{8}$	$\frac{11}{16}$	$1\frac{1}{4}$	$\frac{29}{32}$	30 000	14	24	38
No. 32M-15......	$4 \times 4 \times \frac{3}{8}$	$\frac{13}{16}$	$1\frac{1}{4}$	$\frac{27}{32}$	27 900	15	14.5	29.5
No. 32M-17......	$4 \times 4 \times \frac{3}{8}$	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	26 200	15	22	37
No. 32M-19......	$4 \times 4 \times \frac{3}{8}$	$\frac{17}{16}$	$1\frac{1}{4}$	$\frac{23}{32}$	23 200	12	12	24
No. 32M-11......	$4 \times 4 \times \frac{3}{8}$	$\frac{15}{16}$	1	$\frac{17}{32}$	18 100	10	15	25
No. 32M-9.......	$4 \times 4 \times \frac{3}{8}$	$\frac{15}{16}$	$\frac{3}{4}$	$\frac{9}{32}$	9 500	8	13	21
No. 32M-27......	$2 \times 2 \times \frac{3}{16}$	$\frac{9}{16}$	1	$\frac{23}{32}$	14 400	12	17	29
No. 32M-29......	$2 \times 2 \times \frac{3}{16}$	$\frac{11}{16}$	1	$\frac{21}{32}$	13 950	11	16	27
No. 32M-31......	$2 \times 2 \times \frac{3}{16}$	$\frac{13}{16}$	1	$\frac{19}{32}$	12 250	11	20	31
No. 32M-25......	$2 \times 2 \times \frac{3}{16}$	$\frac{11}{16}$	$\frac{7}{8}$	$\frac{17}{32}$	10 850	8	17	25
No. 32M-23......	$2 \times 2 \times \frac{3}{16}$	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{13}{32}$	8 450	8	9 8	17 8

TABLE XII.—RELATION OF DIAMETER OF HOLE AND EDGE DISTANCE ADOPTED IN THIS STUDY TO MOST SEVERE CONDITIONS USED IN TRANSMISSION TOWER CONSTRUCTION IN ANGLE BEND TESTS OF PUNCHED AND GALVANIZED ANGLES.

Laboratory	Kind of Steel	Size of Angle, in.	Size of Hole, in.	Edge Distance,[a] in.	Edge Material,[b] in.	Maximum Load, lb.	Elongation in 2 in., per cent	Reduction in Thickness, per cent	Merit Number
LARGE SIZE ANGLES									
No. 149M-8...	Open hearth.....	$8 \times 8 \times \frac{3}{4}$	$\frac{15}{16}$[c]	$1\frac{1}{4}$	$\frac{25}{32}$	93 300	18	11.7	29.7
No. 149M-7...	Open hearth.....	$8 \times 8 \times \frac{3}{4}$	$1\frac{3}{16}$[d]	$1\frac{5}{8}$	$\frac{33}{32}$	89 600	21	9.8	30.8
No. 135M-1...	Open hearth.....	$8 \times 8 \times \frac{3}{4}$	$\frac{15}{16}$[c]	$1\frac{1}{4}$	$\frac{25}{32}$	128 300	17.5	8.4	25.9
No. 135M-2...	Open hearth.....	$8 \times 8 \times \frac{3}{4}$	$\frac{15}{16}$[c]	$1\frac{1}{4}$	$\frac{25}{32}$	116 700	1.5	1.2	2.7
No. 135M-7...	Open hearth.....	$8 \times 8 \times \frac{3}{4}$	$1\frac{3}{16}$[d]	$1\frac{5}{8}$	$\frac{33}{32}$	99 600	15	8.4	23.4
No. 132M-1...	Open hearth.....	$8 \times 6 \times \frac{3}{4}$	$\frac{15}{16}$[c]	$1\frac{1}{4}$	$\frac{25}{32}$	99 600	20.5	7.7	28.2
No. 132M-2...	Open hearth.....	$8 \times 6 \times \frac{3}{4}$	$\frac{15}{16}$[c]	$1\frac{1}{4}$	$\frac{25}{32}$	98 200	17.5	12.2	29.7
No. 132M-7...	Open hearth....	$8 \times 6 \times \frac{3}{4}$	$1\frac{3}{16}$[d]	$1\frac{5}{8}$	$\frac{33}{32}$	94 400	19.5	16	35.5
MEDIUM SIZE ANGLES									
No. 36M......	Open hearth.....	$6 \times 6 \times \frac{1}{2}$	$\frac{11}{16}$[c]	$\frac{7}{8}$	$\frac{17}{32}$	59 500	12	14.2	26.2
No. 31M......	Open hearth.....	$6 \times 6 \times \frac{1}{2}$	$\frac{11}{16}$[c]	$\frac{7}{8}$	$\frac{17}{32}$	55 000	14	20	34
No. 70M......	Open hearth.....	$6 \times 6 \times \frac{1}{2}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	59 200	16	13.6	29.6
No. 86M......	Open hearth.....	$4 \times 4 \times \frac{1}{2}$	$\frac{11}{16}$[c]	$\frac{7}{8}$	$\frac{17}{32}$	43 700	12	7.8	19 8
No. 86M-7....	Open hearth.....	$4 \times 4 \times \frac{1}{2}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	31 000	17.5	14	31.5
No. 87M......	Open hearth.....	$4 \times 4 \times \frac{1}{2}$	$\frac{11}{16}$[c]	$\frac{7}{8}$	$\frac{17}{32}$	23 500	12.5	10	22.5
No. 87M-7....	Open hearth.....	$4 \times 4 \times \frac{1}{2}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	24 500	16	14	30.2
No. 119M.....	Duplex..........	$4 \times 4 \times \frac{1}{2}$	$\frac{11}{16}$[c]	$\frac{7}{8}$	$\frac{17}{32}$	36 900	10	11.5	21.5
No. 119M-7...	Duplex..........	$4 \times 4 \times \frac{1}{2}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	25 700	21	5.7	26.7
No. 101M.....	Open hearth.....	$4 \times 4 \times \frac{3}{8}$	$\frac{9}{16}$[c]	$\frac{3}{4}$	$\frac{15}{32}$	21 300	12.5	16.6	29.1
No. 101M-7...	Open hearth.....	$4 \times 4 \times \frac{3}{8}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	21 200	16.5	10.3	26.8
No. 102M.....	Open hearth.....	$4 \times 4 \times \frac{3}{8}$	$\frac{9}{16}$[c]	$\frac{3}{4}$	$\frac{15}{32}$	22 800	7.5	10.2	17.9
No. 102M-7...	Open hearth.....	$4 \times 4 \times \frac{3}{8}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	21 500	15	11.4	26.4
SMALL SIZE ANGLES									
No. 89M-9....	Open hearth.....	$3 \times 3 \times \frac{1}{4}$	$\frac{9}{16}$[c]	$\frac{5}{8}$	$\frac{11}{32}$	9 690	10	11.5	21.5
No. 89M-10...	Open hearth.....	$3 \times 3 \times \frac{1}{4}$	$\frac{9}{16}$[c]	$\frac{5}{8}$	$\frac{11}{32}$	9 750	9.5	11.7	21.2
No. 89M-7....	Open hearth.....	$3 \times 3 \times \frac{1}{4}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	8 600	20.5	14.9	35.4
No. 55M-9....	Open hearth.....	$2\frac{1}{2} \times 2\frac{1}{2} \times \frac{1}{4}$	$\frac{9}{16}$[c]	$\frac{9}{16}$	$\frac{9}{32}$	6 750	8.5	8.5	17.0
No. 55M-10...	Open hearth.....	$2\frac{1}{2} \times 2\frac{1}{2} \times \frac{1}{4}$	$\frac{9}{16}$[c]	$\frac{9}{16}$	$\frac{9}{32}$	6 620	7.5	14.2	21.7
No. 55M-7....	Open hearth.....	$2\frac{1}{2} \times 2\frac{1}{2} \times \frac{1}{4}$	$\frac{13}{16}$[d]	$1\frac{1}{8}$	$\frac{23}{32}$	7 880	14.5	13.8	28.3
No. 107M-9...	Open hearth.....	$2\frac{1}{2} \times 2\frac{1}{2} \times \frac{3}{16}$	$\frac{9}{16}$[c]	$\frac{9}{16}$	$\frac{9}{32}$	4 760	8.0	7.8	15.8
No. 107M-7...	Open hearth.....	$2\frac{1}{2} \times 2\frac{1}{2} \times \frac{3}{16}$	$\frac{13}{16}$[d]	$1\frac{1}{8}$	$\frac{23}{32}$	5 700	21.5	16.5	38.0
No. 108M-9...	Open hearth.....	$2\frac{1}{2} \times 2\frac{1}{2} \times \frac{3}{16}$	$\frac{9}{16}$[c]	$\frac{9}{16}$	$\frac{9}{32}$	4 910	8.5	11.2	19.7
No. 108M-7...	Open hearth.....	$2\frac{1}{2} \times 2\frac{1}{2} \times \frac{3}{16}$	$\frac{13}{16}$[d]	$1\frac{1}{8}$	$\frac{23}{32}$	5 850	22.0	12.0	34.0
No. 130M-9...	Open hearth.....	$2 \times 2 \times \frac{1}{4}$	$\frac{9}{16}$[c]	$\frac{9}{16}$	$\frac{9}{32}$	4 090	8.0	14.7	22.7
No. 130M-7...	Open hearth....	$2 \times 2 \times \frac{1}{4}$	$\frac{11}{16}$[d]	1	$\frac{21}{32}$	5 250	21.0	27.5	48.5
No. 125M-9...	Duplex..........	$2 \times 2 \times \frac{1}{4}$	$\frac{9}{16}$[c]	$\frac{9}{16}$	$\frac{9}{32}$	4 280	10.0	9.4	19.4
No. 125M-7...	Duplex..........	$2 \times 2 \times \frac{1}{4}$	$\frac{11}{16}$[d]	1	$\frac{21}{32}$	5 660	18.0	18.0	36.0
No. 126M-9...	Duplex..........	$2 \times 2 \times \frac{1}{4}$	$\frac{9}{16}$[c]	$\frac{9}{16}$	$\frac{9}{32}$	4 450	8.5	12.0	20.5
No. 126M-7...	Duplex..........	$2 \times 2 \times \frac{1}{4}$	$\frac{11}{16}$[d]	1	$\frac{21}{32}$	5 550	16.5	17.5	34.0

[a] Distance from center of hole to edge of angle.

[b] Distance from outer edge of hole to edge of angle.

[c] Diameter of hole and edge distance according to the most severe conditions used in transmission tower construction.

[d] Values used in this study.

the hole and the edge of the angle. The wider the "bridge" of material, the more elongation is obtained over the gage length; the reduction of area is less affected, but follows the same trend.

In Table XII representative data are given of comparison angle bend tests with the size of hole and edge distance used in this study and with the most severe values in transmission tower codes. For the large size angles, additional data are given in Table IV, to which reference should now be made. In these thick sizes, the hole and edge distance for the 6-in. angles used in the study and in the most severe conditions in transmission tower design coincided exactly; for the 8-in. angles the values in transmission tower design were the more severe. It seems fairly likely, therefore, that the greater amount of brittle behavior, reported in Table IV, in the 6-in. than in the 8-in. angles was due to this difference in the size and location of the punched hole. Here it should be pointed out, however, that the proportion of brittle behavior even in the 8-in. angles, where the less severe conditions were used, was already so great as to make drilling instead of punching highly advisable. The results of the study indicate plainly that if the large angles are drilled (as recommended by Subcommittee X in the Proposed Tentative Recommended Practice for Safeguarding Against Embrittlement of Hot-Galvanized Structural Steel Products and Procedure for Detecting Embrittlement) the use of the severe values of tower practice regarding size of hole and edge distance would have no effect whatsoever in producing brittle behavior. Thus the conclusions of the study with respect to the large angles need no modification when the more severe edge distances are used. Such a change would only tend to further emphasize the need of drilling the large angles.

Returning now to the results of the comparisons for the medium size angles in Table XII, it is readily apparent from the merit numbers obtained that in these angles changing the size of hole and the edge distance had only a minor effect; the lowering of the merit numbers with the more severe conditions was insufficient to cause close approach to brittle behavior.

On the other hand, in the smaller angles the edge material was so much smaller with the more severe conditions that appreciably lower merit numbers were obtained. However, here too there was no near approach to brittle behavior. It should be pointed out that with the smaller holes and thinner edge material of the more severe conditions the elongation at the fracture was localized, so that it took place almost entirely over a 1-in. gage length, whereas with the thicker edge material used in the study, the elongation spread over a good part of the 2-in. gage length.

This is apparent from the results of the angle bend tests in Table XIII, in which the elongations were measured over a 1-in. as well as over a 2-in. gage length. Figure 11 shows the appearance of the fractures of representative specimens from Table XIII. In Fig. 11 it can be seen simply by visual inspection that specimen 129M–9 which measured only 5.5 per cent elongation over a 2-in. gage length (but over 10 per cent over a 1-in. gage length) showed a high degree of deformation at the fracture. In this angle the elongation as expressed in percentage over a 2-in. gage length (and as used in this study and included in the merit numbers of Figs. 6 to 10 and throughout the data in this report) is approximately only one-half of what it actually is in the deformed section, the same being true for other angles of similar size and edge material.

TABLE XIII.—EFFECT OF USING 1-IN. AND 2-IN. GAGE LENGTH ON PERCENTAGE ELONGATION AND MERIT NUMBER.

Small and medium size duplex punched and galvanized angles were used, with the size hole and edge distance of this study and also with the severer conditions used in tower practice.

Laboratory	Size of Angle, in.	Size of Hole, in.	Edge Distance, in.[a]	Edge Material, in.[b]	Elongation				Reduction in Thickness, per cent	Percentage Increase of 1 in. over 2-in. Gage Length	
					1-in. Gage Length		2-in. Gage Length				
					Inches	Per Cent	Inches	Per Cent		Elongation	Merit Number
No. 129M-9	$2 \times 2 \times \frac{1}{4}$	$\frac{9}{16}$[c]	$\frac{9}{16}$	$\frac{9}{32}$	0.10	10	0.11	5.5	8.5	82	32
No. 90M-9	$3 \times 3 \times \frac{1}{4}$	$\frac{9}{16}$[c]	$\frac{5}{8}$	$\frac{11}{32}$	0.15	15	0.15	7.5	7.5	100	50
No. 91M-9	$3 \times 3 \times \frac{1}{4}$	$\frac{9}{16}$[c]	$\frac{5}{8}$	$\frac{11}{32}$	0.17	17	0.19	9.5	5.6	79	50
									Average[c]	87	44
No. 129M-10	$2 \times 2 \times \frac{1}{4}$	$\frac{11}{16}$[d]	1	$\frac{21}{32}$	0.30	30	0.38	19	8.4	58	25
No. 90M-10	$3 \times 3 \times \frac{1}{4}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	0.26	26	0.33	16.5	14.5	57.5	32
No. 91M-10	$3 \times 3 \times \frac{1}{4}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	0.24	24	0.33	16.5	8.8	45.4	29
									Average[d]	53	29
No. 68M-11	$6 \times 6 \times \frac{1}{2}$	$\frac{11}{16}$[c]	1	$\frac{21}{32}$	0.16	16	0.20	10	7.9	60	33.5
No. 68M-12	$6 \times 6 \times \frac{1}{2}$	$\frac{11}{16}$[c]	1	$\frac{21}{32}$	0.17	17	0.19	9.5	7.1	79	45
									Average[c]	70	39
No. 68M-13	$6 \times 6 \times \frac{1}{2}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	0.19	19	0.25	12.5	6.4	52	34
No. 68M-14	$6 \times 6 \times \frac{1}{2}$	$\frac{15}{16}$[d]	$1\frac{1}{4}$	$\frac{25}{32}$	0.15	15	0.23	11.5	6.9	30.5	19
									Average[d]	41	26

[a] Distance from center of hole to edge of angle.

[b] Distance from outer edge of hole to edge of angle.

[c] Diameter of hole and edge distance according to the most severe conditions used in transmission tower construction.

[d] Values used in this study.

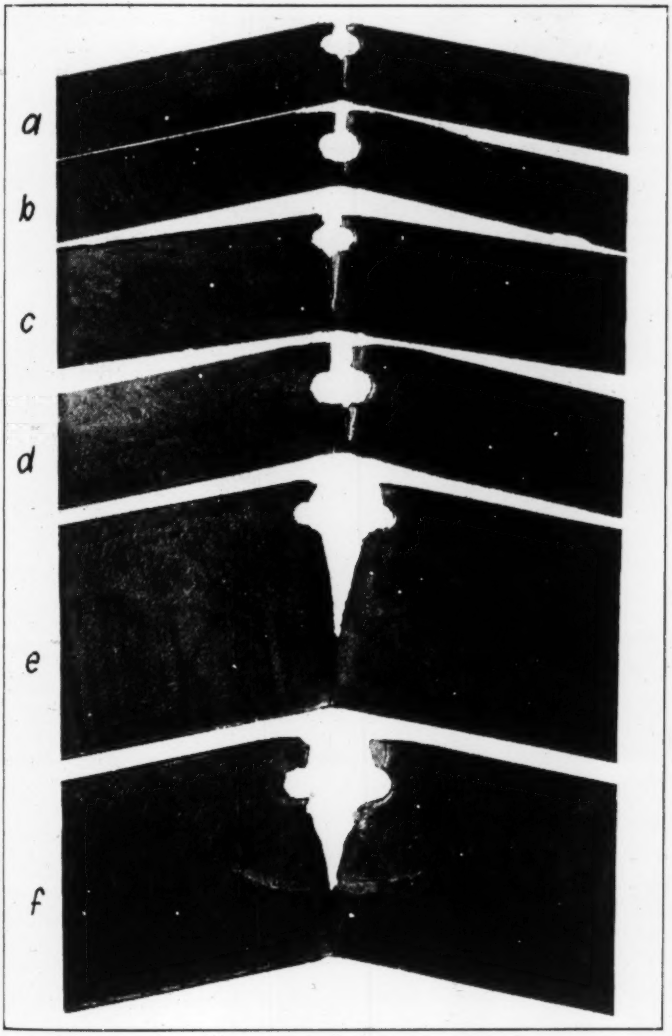

FIG. 11.—Appearance of Fractures of Small and Medium Angle Bend Test Specimens Varying in Size of Hole and Edge Distance.

With the thinner edge material or "bridge" between the hole and edge of the angle the elongation in the small angles was localized over a 1-in. gage length.

(a) Laboratory No. 129 M-9. (b) Laboratory No. 129 M-10. (c) Laboratory No. 90 M-9.
(d) Laboratory No. 90 M-10. (e) Laboratory No. 68 M-11. (f) Laboratory No. 68 M-13.

Gage Length for Measuring Elongation in Angle Bend Test:

From the above it is evident that the results and conclusions of this study, in so far as separating the "sheep" from the "goats" is concerned, would apply without change, irrespective of what sizes of holes and edge distances, as given in Table IX, were used in future embrittlement testing by the angle bend test. Since the angle bend test is so frankly imitative of actual engineering conditions, it would seem advisable to choose the most severe conditions standard for transmission tower construction, that is, the values of either company A or B in Table IX. For the small size angles, it would be preferable, for a hole diameter up to $\frac{11}{16}$ in. and edge distance up to $\frac{3}{4}$ in., to determine the percentage elongation over a 1-in. instead of over a 2-in. gage length. This became apparent when a sufficient mass of data had been collected to allow final tabulation, and when time for close study of sufficient accumulated data was available after the testing work had been brought nearly to completion, but was not fully brought out till the study was made.

IV. ANALYSIS, INTERPRETATION AND ADDITIONAL RESULTS

Having covered the results which are of principal concern from the engineering viewpoint, a more detailed discussion will be given of the rôle played by the factors involved in embrittlement and of their mode of action. For convenience in exposition rather than from any definite view as to their relative importance, the topics to be treated have been arranged in the following order: punching; pickling and galvanizing; temperature of testing; steel. The important factor of the size of the angle, because it appears to depend on the greater severity of the punching operation and on the coarser grain of the steel in the larger angles, will be considered under the two headings; punching and steel. Although the chief aim in this discussion is explanatory, considerable additional data of practical import are introduced, for example, on sub-punching and reaming, on the possibility of heat treatment, and on the very remarkably uniform freedom from embrittlement after punching and galvanizing exhibited, by the few specimens available for study, of the special German structural steel manufactured under the trade name "Izett."

A. PUNCHING

Cold Work:

The process of punching compresses and distorts the metal about the circumference of the hole, and generally starts slight tears and cracks. That cold work very decidedly lowers the notched-bar impact resistance of structural steel, the lowering depending on the degree of cold work (compression or extension) is shown in Fig. 12. It is significant that the steels which show the most rapid fall in impact resistance with cold work are most affected by punching.

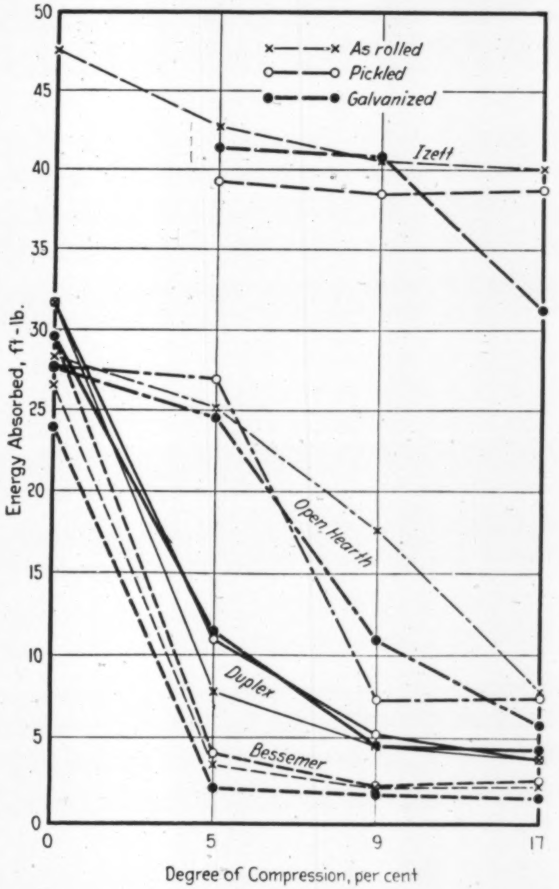

FIG. 12.—Charpy Impact Resistance of Bessemer, Duplex, Open Hearth, and Izett Steel After Different Degrees of Cold Work by Compression.

Impact Test Specimens Cold Worked by Compression and Tension:

Similar impact test results were obtained after cold working either by compression of by extension. Although the scatter in results was about the same for the two types of cold working, it is probable that for greater accuracy cold working by extension is preferable, cold working by compression probably being the more convenient.

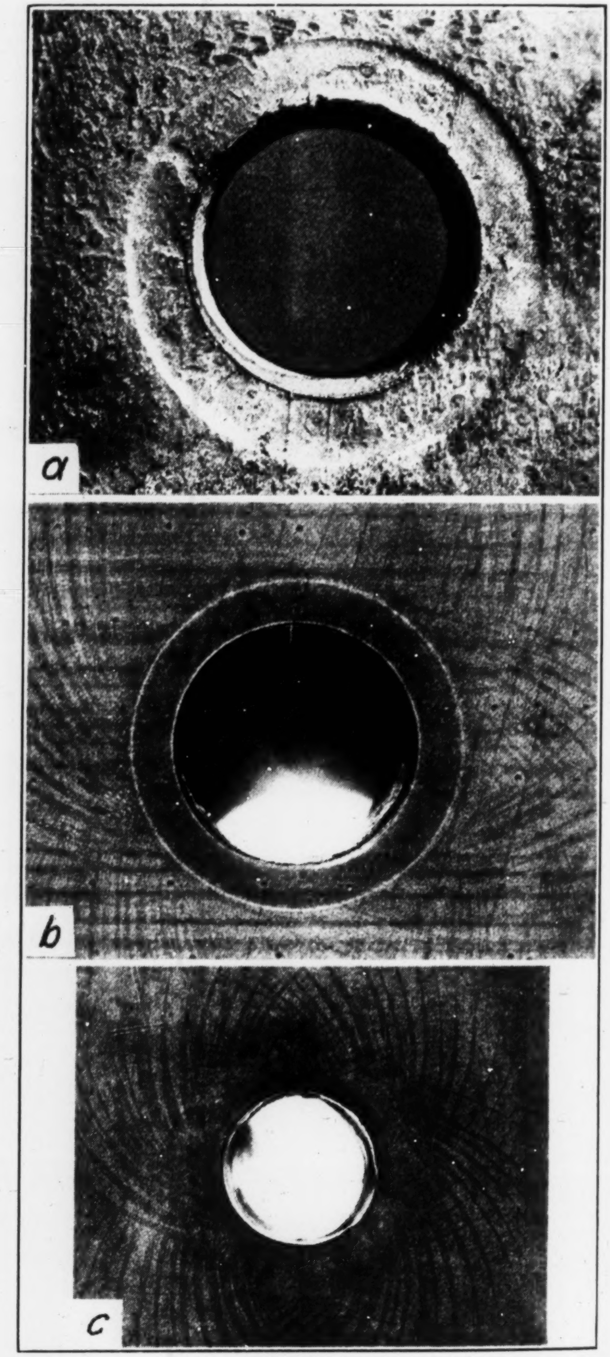

FIG. 13.—Effects of Punching.

(*a*) Depression made by die in punching 8 × 8 × 1 in. angle.

(*b*) Strain lines about punched hole revealed by Fry's reagent in large bessemer angle. Rockwell hardness tests were made near the hole and within and without the strain lines.

(*c*) Strain lines about hole in 6 × 6 × $\frac{1}{2}$ in. bessemer angle.

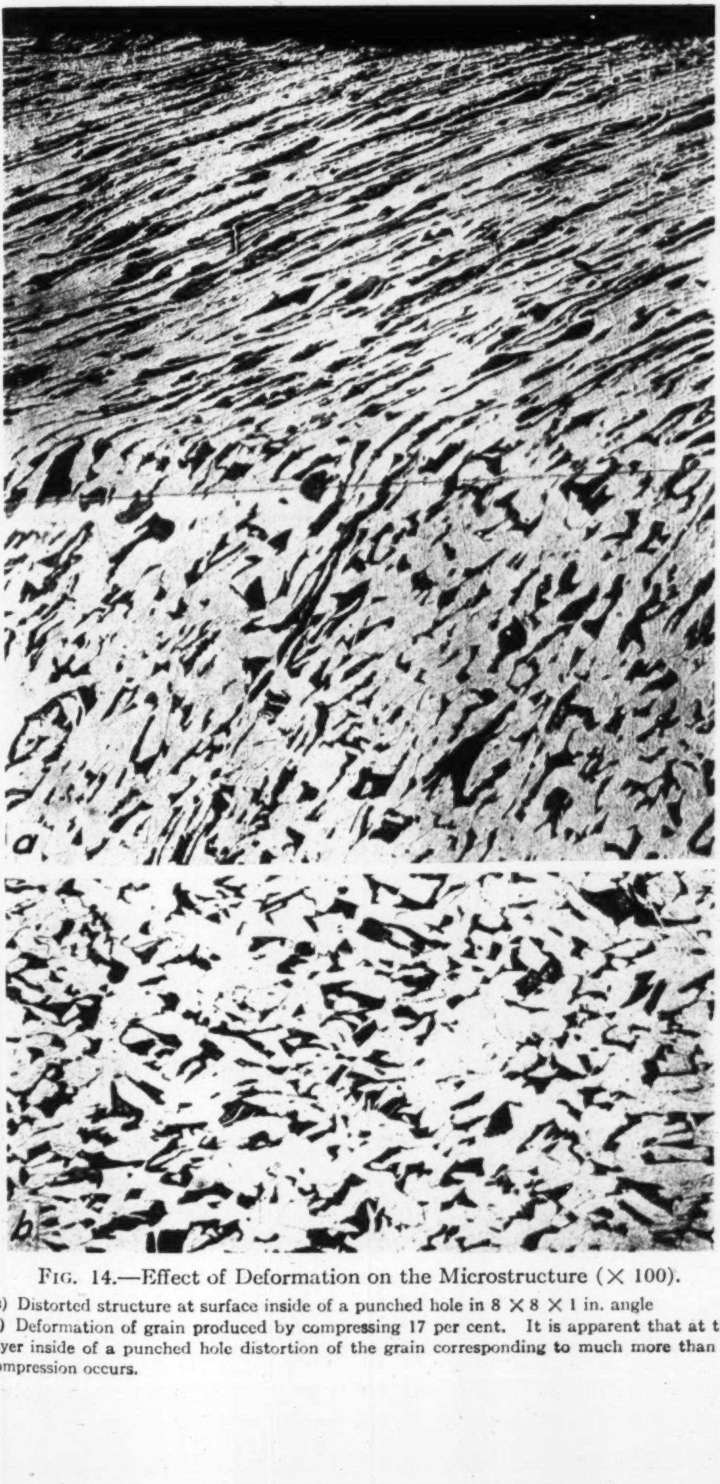

FIG. 14.—Effect of Deformation on the Microstructure (× 100).

(*a*) Distorted structure at surface inside of a punched hole in 8 × 8 × 1 in. angle

(*b*) Deformation of grain produced by compressing 17 per cent. It is apparent that at the surface layer inside of a punched hole distortion of the grain corresponding to much more than 17 per cent compression occurs.

Strain Lines—Grain Distortion:

The depression left by the die in punching (Fig. 13(*a*)), which frequently is fairly deep, is evidence that at least some cold work occurs in punching. Strain or deformation lines extend for a considerable distance about the punched hole (Fig. 13(*b*) and (*c*)) and can be revealed by suitable etching[1] in certain steels, these lines being due to very slight deformations, as will be indicated later. Severe distortion is revealed in the microstructure about the periphery of the hole—distortion considerably greater than that corresponding to 17 per cent compression (Fig. 14(*a*) and (*b*)), but this severely distorted layer is very narrow. As may be judged from Fig. 14(*a*) at a magnification of 100, the most severely distorted layer was not over 0.02 in. deep, and all signs of distortion generally vanished 0.04 in. away from the wall of the hole.

TABLE XIV.—ROCKWELL HARDNESS, "B" SCALE, TESTS IN PROXIMITY TO AND WITHIN PUNCHED HOLES.

The values are representative; results of additional tests have been omitted.

Laboratory	Kind of Steel	Size of Angle, in.	Location of Test	Rockwell Hardness, "B" Scale					
				Surface of Angle Close to Hole ($\frac{1}{16}$ in.)	Longitudinal Section Through Middle of Hole Perpendicular to Surface of Angle		Original Hardness	Increase in Hardness	Degree of Compression Corresponding to Maximum Hardness
					Near Hole ($\frac{1}{16}$ in.)	Within Hole			
No. 397.	Bessemer........	6 × 6 × ½	Punch side..	83.7	85	89.5	....	14	5
			Middle.....	....	89.5	103	75.5	28	25+
			Die side....	87.7	84	98.8	....	23	25
No. 481.	Bessemer.......	8 × 8 × 1	Punch side..	81.8	89.5	89.5	....	18	10
			Middle.....	....	92.5	96	71.5	24	25
			Die side....	85	90	91	....	19	10
No. 251.	Open hearth.....	6 × 6 × ½	Punch side..	71.1	78	92	....	28	25+
			Middle.....	....	85	93.3	63.6	29	25+
			Die side....	75.8	78.8	94.5	....	30	25+
No. 511.	Open hearth.....	8 × 8 × 1	Punch side..	72.6	81	92.5	....	27	25+
			Middle.....	....	88.5	94	65.2	29	25+
			Die side....	76.2	85.5	91.3	....	26	25+

Degree of Cold Work in Punching—Hardness Measurements:

The degree and depth of cold work which occur in punching were also gaged by Rockwell hardness tests at the surface of and along sections through punched holes, as shown in Table XIV. The degree of cold work corresponding to the Rockwell hardness readings was determined from Fig. 15, which indicates the increases in hardness obtained in bessemer, duplex, open-hearth, and Izett steel after various amounts of compression.

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[1] A. Fry, "Strain Line Etching," *Stahl und Eisen*, Vol. 41, p. 1093 (1921).

The hardness measurements were made on the surfaces of the angles about $\frac{1}{16}$ in. from the punched hole on the punch and die side, and also on a longitudinal section through the middle of the hole. These latter readings were taken near the surfaces of the angle (inside the hole and about $\frac{1}{16}$ in. from the hole) as well as in the middle between the two surfaces where the greatest distortion and tearing in punching generally occur. As shown in Table XIV the maximum increases in hardness corresponded with over 25 per cent cold work by compression, which is in agreement with the evidence provided by the microstructure. As would be expected, the surface hardness was greater on the die side than on the punch side.

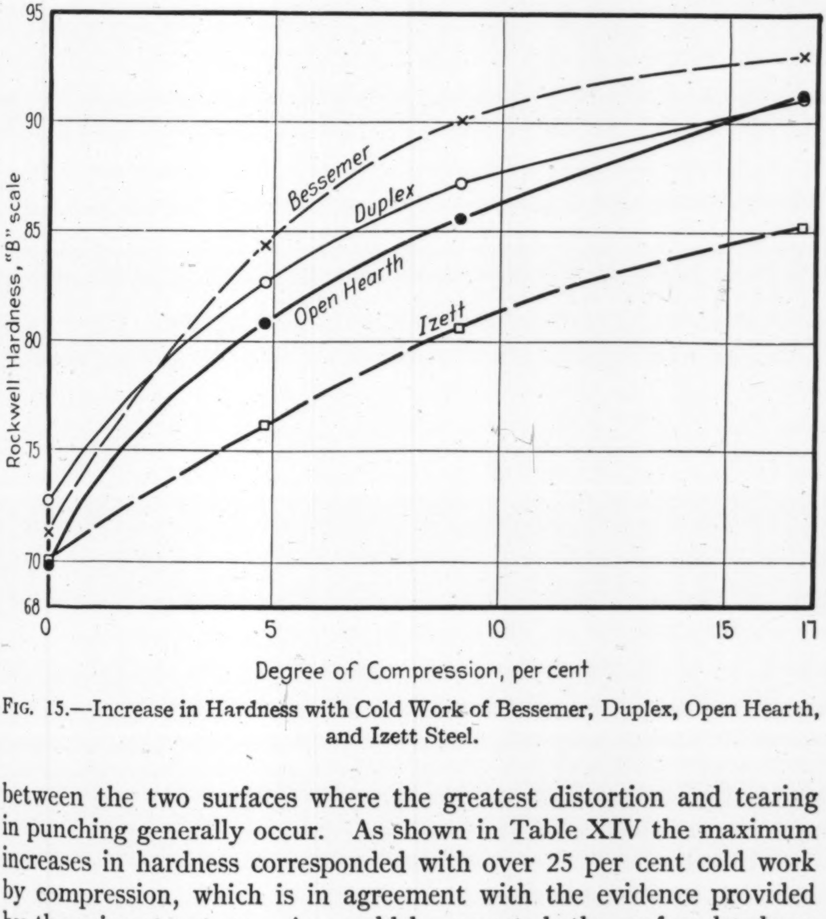

FIG. 15.—Increase in Hardness with Cold Work of Bessemer, Duplex, Open Hearth, and Izett Steel.

The maximum hardness inside the hole was as high in the $6 \times 6 \times \frac{1}{2}$ in. angles as in the $8 \times 8 \times 1$ in. angles, but, as indicated in the readings on the longitudinal sections, the hardening due to cold work about $\frac{1}{16}$ in. away from the hole was greater in the larger angles, that is, fairly severe cold working extended deeper in the larger angles. This probably accounts in part for the importance of the factor of size of angle in embrittlement.

Hardness readings were also taken inside of the strain lines about a punched hole, as illustrated in Fig. 13(*b*). A slight increase in hardness in the area showing strain lines was observed, but this was much smaller than occurs directly about the punched hole, and corresponded to a degree of cold working by compression of less than 2 per cent.

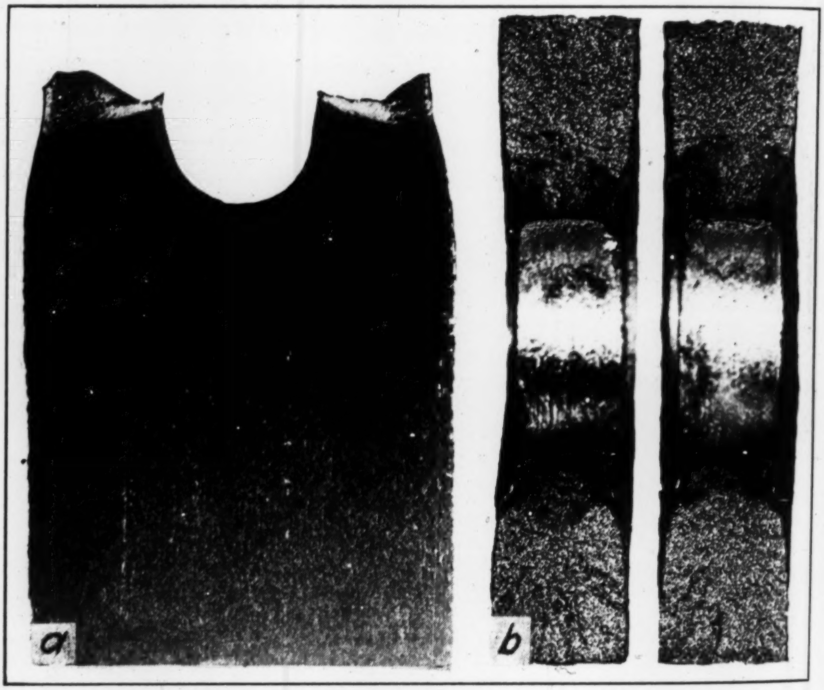

FIG. 16.—Hole Tension Specimens Compressed with a Circular Die and Hole Drilled Out in Compressed Portion.

(*a*) Silky fracture in duplex, as rolled specimen, compressed 20 per cent. Note the depression made by the die in compressing 20 per cent.

(*b*) Crystalline fracture in duplex, galvanized specimen, compressed 20 per cent.

Impact Tests near Rim of Punched Hole:

In Charpy impact tests of specimens cut about $\frac{1}{8}$ in. from a punched hole, no lowering in impact resistance occurred, except in the bessemer steel after galvanizing. Evidently $\frac{1}{8}$ in. away from the hole the effect of the cold work in punching on the impact resistance is already negligible. Frémont[1] using tiny notched-bar test specimens cut very close to punched holes found a decided decrease in impact resistance.

Tearing and Cracking—Mechanism of Fracture:

To determine whether cold work alone without the accompanying tearing and cracking which occur in punching would cause a lowering in ductility in a test similar to the angle bend test, hole tension specimens were compressed on both sides to various degrees in a die, the compressed circular areas being $\frac{1}{4}$ in. larger in diameter than the hole required. A hole was then drilled in the center of the depression leaving it surrounded by a cold-worked rim. The specimens were tested in the as rolled condition and after galvanizing. Figure 16 indicates that the embrittlement resulting from this sort of cold work was similar to that in punching. The ductility after compressing and drilling, however, did not fall as low as after punching, more probably because the degree of compression used was not so severe as the maximum occurring in punching, but possibly also because the tearing and cracking in punching may play some part in causing embrittlement. Crystalline fractures were produced after compressing and galvanizing as illustrated in Fig. 16(*b*). It is a curious fact that in the compressed portion (and it is the compression, of course, which causes the brittle behavior) the fracture is not brittle

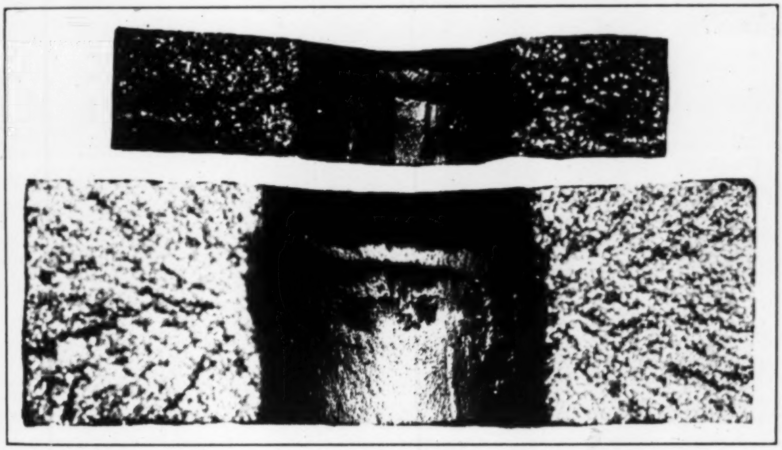

FIG. 17.—Cracks and Tears Inside of Punched Holes in 6 × 6 × $\frac{1}{2}$ in. and 8 × 8 × 1 in. Angles. Note that the walls of the punched holes are not parallel; the hole is considerably bigger on the die side than on the punch side.

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[1] C. Frémont, "Cutting and Punching of Metal," *Bulletin*, Soc. Encouragement Industrie Nationale, Vol. 128, p. 563 (1929).

in appearance, but ductile, the brittle portion of the fracture beginning beyond the compressed area. This same phenomenon has been observed occasionally in punched angle bend and hole tension tests. It has been observed in pulling the hole tension test specimens that the fracture starts at the edge of the punched hole and progresses through the cold worked material as an extremely sharp notch; this may cause the fracture which continues through the unworked material to ultimate failure to be crystalline.

Notch Propagation—"Trennfestigkeit":

Tears and cracks produced in punching occurred to an equal extent in all the steels studied (bessemer, duplex, open-hearth and Izett), Fig. 17 being typical of the appearance of such tears and cracks. It might seem therefore that, since tears form equally in steels which show high and low susceptibility to embrittlement in punching, the tears are probably not very directly involved. However, it is also possible that similar tears and cracks would affect different steels differently; that is, the steels might vary in their susceptibility to notch propagation. Thus in tension test results on notched specimens, the strength increased at a greater rate in bessemer steel than in open-hearth steel as the depth of the notch increased. Likewise, to compare the Charpy impact test data in Table XV with those in Table I (V-notches being used in Table XV and circular notches in Table I), it is evident that the sharper V-notch had an effect in lowering the impact resistance of the bessemer steel but not of the duplex and open-hearth steels. However, the fact brought out below that heat treatment after punching (even to the comparatively low temperature of 1200° F. (650° C.) which would hardly be considered to heal any cracks formed) completely eliminated the embrittling effect of punching, indicates that the cracks formed

TABLE XV.—CHARPY AND IZOD V-NOTCH BAR IMPACT TESTS OF SPECIMENS FROM 6 × 6 × ½ IN. ANGLES.

Laboratory	Kind of Steel	Energy Absorbed, ft-lb.[a]			
		Charpy Specimens			Izod Specimens Rolled
		Rolled	Pickled	Galvanized	
No. 194	Bessemer	10.9	9.6	5.7	13.7
No. 238	Duplex	37	38.2	39	36.8
No. 289	Open hearth	32.9	30.5	37.2	40

[a] Average of three tests.

in punching have a rather minor embrittling effect. The evidence indicates that by far the major cause of the embrittlement in punching lies in the accompanying cold work.

Removal of Cold Worked Material by Reaming:

Although strain lines produced by punching may extend for a considerable distance from the hole, the degree of cold work within the strain lines as we have seen is so small, below 2 per cent, as to have virtually no embrittling effect. The severely cold-worked layer about the hole, on the other hand, is so narrow that it can be removed readily by reaming. The results of angle bend and hole tension tests after sub-punching and reaming in Table XVI indicate that the

TABLE XVI.—RESULTS OF ANGLE BEND AND HOLE TENSION TESTS TO SHOW THE EFFECT OF SUB-PUNCHING AND REAMING THE HOLE.

The tests were made after galvanizing. The values are representative of 86 tests.

Laboratory	Kind of Steel	Size of Angle, in.	Hole	Maximum Load, lb.	Elongation in 2 in., per cent	Reduction in Thickness, per cent	Merit Number
			HOLE TENSION TESTS				
No. 110-4...	Duplex.........	8 × 8 × 1	Punched[a].................	81 800	2.5	2.5	5
No. 115-3...	Duplex.........	8 × 8 × 1	Sub-punched and reamed[b]..	129 200	24	18.5	42.5
No. 115-4...	Duplex.........	8 × 8 × 1	Sub-punched and reamed[c]..	127 100	16.5	10.4	26.9
No. 120-4...	Duplex.........	8 × 8 × 1	Drilled[a].................	124 600	23	20.9	43.9
No. 94-4....	Open hearth.....	8 × 8 × 1	Punched[a]................	95 300	2	2.9	4.9
No. 95-3....	Open hearth.....	8 × 8 × 1	Sub-punched and reamed[b]..	121 500	27	20.8	47.8
No. 95-4....	Open hearth.....	8 × 8 × 1	Sub-punched and reamed[c]..	119 000	23	19.6	42.6
No. 74-4....	Open hearth.....	8 × 8 × 1	Drilled[a].................	121 300	24 5	29.3	53.8
No. 155-4...	Bessemer........	6 × 6 × ½	Punched[d].................	26 400	1	0	1
No. 152-4...	Bessemer........	6 × 6 × ½	Sub-punched and reamed[e]..	49 500	15.5	31.8	47.3
No. 146-4...	Bessemer.......	6 × 6 × ½	Drilled[d]..................	49 200	13.5	26.9	40.4
			ANGLE BEND TESTS				
No. 175.....	Bessemer.......	6 × 6 × ½	Punched[d].................	45 000	3.5	8	11.5
No. 177.....	Bessemer.......	6 × 6 × ½	Sub-punched and reamed[e]..	63 800	20	24	44
No. 158.....	Bessemer.......	6 × 6 × ½	Drilled[d]..................	66 400	12	14	26
No. 201.....	Duplex.........	6 × 6 × ½	Punched[d]..................	58 900	13.5	17.1	30.6
No. 200.....	Duplex.........	6 × 6 × ½	Sub-punched and reamed[e]..	64 700	22.5	23.2	45.7
No. 222.....	Duplex.........	6 × 6 × ½	Drilled[d]..................	64 800	24	20	44

[a] Punched or drilled $\frac{17}{16}$ in.
[b] Punched $\frac{13}{16}$ in.; reamed to $\frac{17}{16}$ in.
[c] Punched $\frac{15}{16}$ in.; reamed to $\frac{17}{16}$ in.
[d] Punched $\frac{13}{16}$ in. or drilled to $\frac{13}{16}$ in.
[e] Punched $\frac{9}{16}$ in.; reamed to $\frac{13}{16}$ in.

removal of a layer of metal about $\frac{1}{16}$ in. thick from the periphery of the hole after punching, although it may not in every case bring the ductility up to the value after drilling, is ample to overcome any tendency toward injurious embrittlement.

Breaking Load with Punched and Drilled Holes:

In Table XVI it may be observed that the maximum loads after sub-punching and reaming or after drilling are considerably higher than after punching. The loads withstood by specimens with drilled holes and by specimens with punched holes are also shown in Table XVII. In large size angles an average increase of about 30 per cent in breaking strength about the hole is gained by drilling instead of punching, which may not be without significance from the standpoint of engineering design.

TABLE XVII.—RESULTS OF ANGLE BEND AND HOLE TENSION TESTS OF LARGE ANGLES SHOWING INCREASE IN BREAKING LOAD OF DRILLED AND PUNCHED SPECIMENS.

Laboratory	Kind of Steel	Size of Angle, in.	Kind of Test	Condition	Maximum Load, lb.		Percentage Increase	Average Percentage Increase
					Punched Hole	Drilled Hole		
No. 109....	Duplex.......	8 × 8 × 1	Angle bend....	As rolled....	124 000	140 000	12.9	....
No. 76.....	Open hearth...	8 × 8 × 1	Angle bend....	As rolled....	128 000	150 600	17.2	....
No. 73M...	Open hearth...	$6 \times 6 \times \frac{3}{4}$	Angle bend....	As rolled....	63 080	95 000	50.5	26.9
No. 110....	Duplex.......	8 × 8 × 1	Hole tension..	As rolled....	99 400	122 100	22.8	....
No. 573....	Open hearth...	8 × 8 × 1	Hole tension..	As rolled....	102 600	119 400	16.6	....
No. 94.....	Open hearth...	8 × 8 × 1	Hole tension..	As rolled....	103 800	119 900	15.5	18.3
No. 73M...	Duplex.......	$6 \times 6 \times \frac{3}{4}$	Angle bend....	Galvanized..	66 500	98 000	47	....
No. S-11...	Open hearth...	$8 \times 8 \times \frac{7}{8}$	Angle bend....	Galvanized..	101 900	135 000	33	....
No. S-13...	Open hearth...	$8 \times 8 \times \frac{7}{8}$	Angle bend....	Galvanized..	109 100	138 600	27	35.8
No. 110....	Duplex.......	8 × 8 × 1	Hole tension...	Galvanized..	81 800	124 600	52	....
No. 41M...	Open hearth...	$8 \times 8 \times \frac{7}{8}$	Hole tension...	Galvanized..	91 500	120 000	31.2	....
No. 41M...	Open hearth...	$8 \times 8 \times \frac{7}{8}$	Hole tension...	Galvanized..	91 300	124 000	35.8	39.6
							Average.....	30.1

Heat Treatment Before Punching:

In regard to the possibility of overcoming the effects of punching by heat treatment, the results obtained indicated that such treatment of the angles before punching was without appreciable benefit. After punching, however, the injury in punching could be readily removed by heat treatment, the principal objection to its use being that of cost. While ship and bridge engineers have sometimes resorted to heat treatment of structural steel, it is generally considered that heat treatment would be impractical for ordinary uses. However, on the Pacific Coast a good deal of experimental work on a commercial scale has recently been done on the heat treatment of low carbon structural steel.[1]

In Table XVIII, giving Charpy impact values before and after heat treatment of the large angle which failed during erection of a transmission tower, a point of interest is the low impact values at the heel, probably due to the large grain size which was observed in this part of the angle. Upon water quenching or air cooling from above the critical range the impact values were greatly increased, but they were not changed on quenching from below the critical range. As shown in Table XIX, however, air cooling from above the critical range before punching appeared to be without material benefit in the angle bend test. The same was true on quenching from 1200° F. (650° C.) before punching. The latter treatment was tried because of the aid of such a treatment in preventing galvanizing embrittlement

TABLE XVIII.—EFFECT OF HEAT TREATMENT OF $8 \times 8 \times \frac{15}{16}$ IN. ANGLE OF DUPLEX STEEL WHICH FAILED DURING ERECTION OF A TRANSMISSION TOWER, ON THE CHARPY IMPACT RESISTANCE.

The values are representative of 54 tests made on specimens from this angle.

	ENERGY ABSORBED, FT-LB.			
PART OF ANGLE	AS RECEIVED	QUENCHED 1630° F. (885° C.) QUENCHED 1425° F. (775° C.) DRAWN 1150° F. (620° C.)	AIR COOLED FROM 1630° F. (885° C.)	QUENCHED FROM 1200° F. (650° C.)
Heel..........	6.5	53.7	37.9	6.6
Toe..........	26.7	54.3	35.5	24.8

TABLE XIX.—ANGLE BEND TESTS TO SHOW THE EFFECT OF NORMALIZING (AIR COOLING FROM 1650° F., 900° C.) BEFORE PUNCHING.

Specimens from $6 \times 6 \times \frac{1}{2}$ in. angles tested after galvanizing. The values are representative of 12 tests.

LABORATORY	KIND OF STEEL	HEAT TREATMENT	MAXIMUM LOAD, LB.	MERIT NUMBER
No. 162..........	Bessemer.........	Normalized.......	40 300	1.8
No. 165..........	Bessemer.........	Not treated......	35 800	1.2
No. 242..........	Duplex...........	Normalized.......	55 200	26.2
No. 245..........	Duplex...........	Not treated......	55 000	16
No. 292..........	Open hearth......	Normalized.......	52 000	31.4
No. 295..........	Open hearth......	Not treated......	50 500	28

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[1] P. F. Lee and H. A. Schade, "Structural Steel Heat Treated," *The Iron Age*, Vol. 125, p. 510 (1930); also W. J. Crook, "Heat Treatment of Low Carbon Steel," *Metal Progress*, Vol. 18, No. 4, p. 47 (1930).

in malleable iron,[1] it being now fairly common practice to quench malleable iron castings from about 1200° F. (650° C.) before pickling and galvanizing. However, from the evidence given above it is plain, even if quenching from 1200° F. (650° C.) were beneficial in increasing the ductility of structural steel (which appears rather doubtful from the values in Table XVIII) that any such benefit disappears in the subsequent punching operation.

Rolling and Straightening Temperatures:

Just as there is a lack of material benefit from heat treatments before punching, there is probably an equal lack of injury. Ordinary variations in the rolling and finishing temperatures probably have little effect on the ductility about the punched hole, even though too low rolling temperatures are reported to reduce the notch-bar impact resistance;[2] the effect of punching the hole is undoubtedly so great as to overshadow the small effects of other ordinary variables on the steel. Since galvanizing embrittlement appears to be due essentially to cold work followed by heating to the blue-brittle region, it was suggested that straightening angles after rolling while they were at blue heat might cause embrittlement. The impact test data in Table XX do indicate that cold work at 300° C. (570° F.) reduces the impact resistance to lower values than cold working at room temperature. However, the fact that in the angle bend test brittleness is only encountered about the punched hole, where very severe cold

Table XX.—Charpy Impact of Specimens Compressed at Room Temperature and at 300° C. (572° F.).

		Energy Absorbed, Ft-lb.[a]			
Kind of Steel	Compressed at	No Compression	5 per cent Compression	9 per cent Compression	17 per cent Compression
Bessemer	25° C. (77° F.)	26.5	3.4	2.2	2.3
Bessemer	300° C. (572° F.)		1.3	1.1	1.4
Duplex	25° C. (77° F.)	31.5	7.8	4.8	4
Duplex	300° C. (572° F.)		3.7	1.9	2.2
Open hearth	25° C. (77° F.)	28.4	25.2	17.7	8
Open hearth	300° C. (572° F.)		5.6	3.9	3.5

[a] Average of three tests.

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[1] L. H. Marshall, "Embrittlement of Malleable Cast Iron Resulting from Heat Treatment," U. S. Bureau of Standards *Technologic Paper No. 245*, Vol. 17, p. 677 (1923).

L. H. Marshall, "A Process for the Prevention of Embrittlement in Malleable Cast-Iron," *Preprint No. 1562-C*, Am. Inst. Mining and Metallurgical Engrs., 8 pp. (1926). Abstracted in *Mining and Metallurgy*, Vol. 7, p. 264 (1926).

[2] K. Wallmann, "Influence of Rolling and Annealing on the Strength of Large Steel Plates," *Zeitschrift* des Vereines Deutscher Ingenieure, Vol. 75, p. 368 (1931).

work and distortion occur—much greater than would result during straightening, and that brittleness is never encountered with drilled holes—indicates that the effect of straightening on embrittlement must be negligible. The possibility of straightening strains being responsible for the scatter observed in the angle bend test of large punched angles may perhaps be worth some consideration, but this also seems extremely doubtful.

Heat Treatment After Punching:

After the punching operation, however, normalizing (air cooling) from above the critical range or from 1200° F. (650° C.) (Table XXI) produced a marked improvement in ductility and appeared sufficient to eliminate the possibility of injurious embrittlement.

TABLE XXI.—ANGLE BEND TESTS TO SHOW THE EFFECT OF NORMALIZING AFTER PUNCHING.

Specimens from 6 × 6 × ½ in. angles tested after galvanizing.

LABORATORY	KIND OF STEEL	HEAT TREATMENT	MAXIMUM LOAD, LB.	MERIT NUMBER
		NORMALIZED (AIR COOLED FROM 1650° F., 900° C.)[a]		
No. 171	Bessemer	Normalized	57 500	37.5
No. 175	Bessemer	Not treated	41 500	11.5
No. 218	Duplex	Normalized	59 200	39
No. 225	Duplex	Not treated	52 000	16.8
No. 268	Open hearth	Normalized	62 000	45
No. 275	Open hearth	Not treated	54 600	24.5
		LOW TEMPERATURE NORMALIZED (AIR COOLED FROM 1200° F., 650° C.)		
No. 473	Open hearth	Normalized	57 600	58.7
No. 471	Open hearth	Not treated	54 000	32.6
No. 474	Open hearth	Normalized	56 900	61.5
No. 472	Open hearth	Not treated	53 000	27.5

[a] The values are representative of 24 tests.

Galvanized Hardware:

The embrittlement of line hardware by cold working followed by galvanizing has been given some consideration in this study. It is now rather generally recognized that cold-headed bolts should be annealed or otherwise stress relieved before galvanizing. Two methods are obviously available for removing the effects of cold working, first, heating to a high drawing temperature, such as 1200° F. (650° C.), and second, annealing or normalizing by heating above the critical range, about 1600 to 1650° F. (870 to 900° C.). In fact, heating to any temperature within the range of 1200 to 1650° F. (650 to 900° C.) should remove the effect of cold working and, therefore, avoid embrittlement in galvanizing. Heating to the higher temperature causes some oxidation and possibly some loss in strength, but inquiries among manufacturers indicated that they had no objection to using the higher temperatures and that 1400 to 1600° F. (760 to 870° C.) is extensively used. Embrittlement of line hardware presents some rather complicated problems, because steel for such purposes is purchased under less strict specifications than in the case of structural angles, and the chances of getting bessemer or off-analysis steels into production are greater. As an illustration of this trouble, one of the samples of embrittled hardware which was examined contained 0.177 per cent sulfur and 0.098 per cent phosphorus, indicating that it was made from bessemer steel. The cold working (cold heading of bolts, sharp bending, etc.) in the making and shaping of line hardware may be quite severe without this fact being recognized by the manufacturer or the user. Finally, there are no established methods for testing such products for embrittlement, and it is difficult to set up standard testing methods. The general practice of heat treating all cold-formed line hardware previous to galvanizing is to be recommended. English investigators of embrittlement of chain have recently recommended that work-hardened steel chain be annealed between 1600 and 1650° F. (870 and 900° C.).[1]

TABLE XXII.—ANGLE BEND TESTS TO SHOW EFFECT OF BAKING 6 × 6 × ½ IN. ANGLES 8 HOURS AT 300° F. (150° C.).

LABORATORY	KIND OF STEEL	TREATMENT	MAXIMUM LOAD, LB.	MERIT NUMBER
No. 401	Bessemer	Punched, then baked	41 800	1
No. 402	Bessemer	Punched, then baked	41 100	0.5
No. 403	Bessemer	Punched, galvanized, baked	41 400	2
No. 404	Bessemer	Punched, galvanized, baked	43 700	0
No. 405	Bessemer	Punched, baked, galvanized	42 000	2
No. 406	Bessemer	Punched, baked, galvanized	51 500	5
No. 475	Open hearth	Punched, baked, galvanized	55 300	30.1
No. 471	Open hearth	Punched, not treated, galvanized	54 000	32.6

"Baking" and Storing:

While on the subject of heat treatment, the data in Table XXII are of interest as showing that prolonged baking at 300° F. (150° C.) after punching and either before or after galvanizing does not remove embrittlement in bessemer steel, as was alleged before the present study was begun.[1] Open-hearth steel also appeared to be unaffected by this baking treatment.

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[1] H. A. Thomas, "Effects of Annealing on Chains," *Transactions*, Nat. Safety Council, Vol. I, p. 281 (1930).

Data obtained in this investigation indicate that storing after rolling is without effect on embrittlement, which is in line with the conclusion previously mentioned that the effect of punching the hole is so great as to mask all other ordinary variables in the steel.

Annealing by Local Electric Resistance Heating:

The fact that the injury due to punching is confined to a very thin ring about the hole suggested, by analogy with reaming, locally annealing the severely cold worked steel about the punched hole. This was successfully accomplished by electric resistance heating of the rim of the punched hole in a 25 kva. welding machine using two copper electrodes slightly larger than the punched hole faced with several thicknesses of copper gauze for better contact. After such heating, as shown in Table XXIII, injurious embrittlement was entirely overcome and high ductility about the punched hole obtained. The time of heating was short and should be greatly reduced by a properly designed higher capacity machine for supplying the electric current. It would seem that the development of some procedure of locally heating large angles to overcome the injury in punching offers possibilities as an alternative method to drilling or sub-punching and reaming.

TABLE XXIII.—HOLE TENSION TESTS SHOWING EFFECT OF LOCAL HEATING BY ELECTRICAL RESISTANCE ABOUT THE PERIPHERY OF PUNCHED HOLES.

Punched 8 × 8 × 1 in. duplex galvanized angles were used in these tests.

Laboratory	Treatment	Testing Temperature, deg. Cent.	Testing Temperature, deg. Fahr.	Maximum Load, lb.	Merit Number
No. 510-4	Punched, not heated	25	77	75 800	2.9
No. 510-3	Punched, not heated	25	77	83 700	1.5
No. 510-2	Punched, not heated	25	77	78 900	1
No. 510-1	Punched, not heated	25	77	84 100	2.2
No. 498-2	Punched and heated 65 seconds	25	77	123 900	34.3
No. 498-1	Punched and heated 110 seconds	0	32	130 400	32.4
No. 496-1	Punched and heated 105 seconds	0	32	132 000	44.4

B. PICKLING AND GALVANIZING

Pickling—Hydrogen Absorption:

The embrittling effect of pickling, particularly in sheet and wire is well known.[2] For this reason and possibly also because the mechanism of such embrittlement, as being due to hydrogen absorption, is generally accepted, whereas the theories in regard to galvanizing embrittlement are still rather unfamiliar, the tendency was at first to attribute the embrittlement in galvanizing mainly to the accompanying pickling. However, the results of this study have indicated that the pickling process is virtually without influence on embrittlement of galvanized structural steel angles.

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[1] V. F. Hammel, *et al.*, Report of Subcommittee X on Embrittlement Investigation, *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part I, p. 212 (1931).

[2] S. C. Langdon and M. A. Grossmann, "The Embrittling Effects of Cleaning and Pickling upon Carbon Steels," *Transactions*, Am. Electrochemical Soc., Vol. 37, p. 543 (1920). Discussion, p. 576.

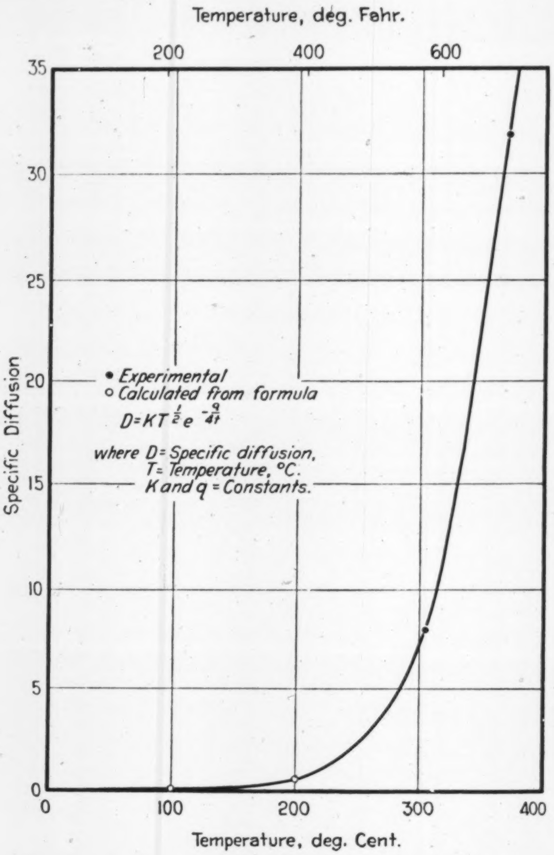

FIG. 18.—Change of Rate of Diffusion of Hydrogen Through Zinc with Temperature.

Diffusion of Hydrogen Through Zinc:

The effect of pickling is known to "wear off" on standing, apparently due to the escape of occluded hydrogen, and the rate of recovery of ductility is accelerated by heating at moderate temperatures, so that at about 150° C. (300° F.) substantial recovery of the original ductility occurs in about ten minutes. It might be assumed, therefore, that any embrittling effect of pickling might be overcome during the heating in the galvanizing bath, as it is very unlikely that the escape of hydrogen would be hindered by the molten zinc. Figure 18, showing the rate of diffusion of hydrogen through zinc (calculated from the data of Hendricks and Ralston)[1] indicates that the diffusion increases sharply with rising temperature, so that it becomes extremely rapid at the melting point of zinc. Van de Loo, as a result of recent work,[2] concluded that heating as in galvanizing for about a minute eliminates the embrittling effect of pickling.

TABLE XXIV.—RELATION OF GALVANIZING TO GALVANIZING WITHOUT PICKLING—RESULTS OF ANGLE BEND AND HOLE TENSION TESTS OF PUNCHED ANGLES AFTER PICKLING AND GALVANIZING AND AFTER GALVANIZING WITHOUT PICKLING.

These values are representative of 26 tests.

Laboratory	Size of Angle, in.	Kind of Steel	Merit Number		
			As Rolled	Pickled and Galvanized	Galvanized Without Pickling
		ANGLE BEND TEST			
No. 96	$8 \times 8 \times 1$	Duplex	32	15.6	2
No. 103	$8 \times 8 \times 1$	Duplex	28.6	3.3	1.6
No. 548	$6 \times 6 \times \frac{1}{2}$	Open hearth	31	29.2	24.3
No. 549	$6 \times 6 \times \frac{1}{2}$	Open hearth	31	31.9	29.7
		HOLE TENSION TEST			
No. 94	$8 \times 8 \times 1$	Open hearth	30	5	10
No. 228	$6 \times 6 \times \frac{1}{2}$	Duplex	30	29	22
No. 438	$6 \times 6 \times \frac{1}{2}$	Duplex	30	24	22
No. 463	$6 \times 6 \times \frac{1}{2}$	Open hearth	34	24.4	23.9

Galvanizing Without Pickling:

However, the most convincing evidence that any embrittlement which might ensue during pickling has practically no effect in lowering the ductility of the finished galvanized angle was obtained in a series of comparison angle bend and hole tension tests of specimens galvanized in the ordinary way after pickling and of others galvanized without pickling. As shown in Table XXIV, the values after galvanizing without pickling were as low as after ordinary galvanizing, and in particular in the large size angles galvanizing without pickling was enough to cause injurious embrittlement.

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[1] B. C. Hendricks and R. R. Ralston, "The Permeability of Hot Metals to Hydrogen," *Journal*, Am. Chemical Soc., Vol. 51, p. 3278 (1929).

[2] H. Van de Loo, W. Püngel and E. H. Schulz, "The Effect of Pickling and Galvanizing on the Strength of Drawn Steel Wire," *Stahl und Eisen*, Vol. 51, p. 1585 (1931).

Excessive Pickling:

It was also suggested that instances of injurious embrittlement might possibly have been caused by excessive pickling, such as would occur if an angle were forgotten in the pickling bath overnight. The results in Table XXV show, however, that excessively long pickling produced no indications of injurious embrittlement; in fact, very high merit numbers were obtained after such treatment. No inhibitor was used in the pickling bath in these tests nor in any of the tests reported in this study.

TABLE XXV.—EFFECT OF EXCESSIVE PICKLING (OVERNIGHT) ON ANGLE BEND TESTS OF PUNCHED OPEN-HEARTH STEEL.

LABORATORY	SIZE OF ANGLE, IN.	TREATMENT	MAXIMUM LOAD, LB.	MERIT NUMBER
No. 88M	4 × 4 × ½	As rolled	27 300	28.8
No. 88M-9	4 × 4 × ½	Pickled 24 hours	21 200	46.8
No. 253	6 × 6 × ½	As rolled	54 500	31
No. 254	6 × 6 × ½	Pickled ½ hour	52 000	22
No. 246	6 × 6 × ½	Pickled 24 hours	52 300	32.2
No. 255	6 × 6 × ½	Pickled ½ hour and galvanized	52 400	20
No. 249	6 × 6 × ½	Pickled 24 hours and galvanized	51 500	30
No. 250	6 × 6 × ½	Pickled 24 hours and galvanized	53 400	30.3

TABLE XXVI.—ANGLE BEND TESTS TO SHOW THE EFFECT OF STORING AFTER PICKLING.

Punched duplex angles were used in these tests.

The values are representative of 38 tests.

LABORATORY	SIZE OF ANGLE, IN.	TREATMENT	MAXIMUM LOAD, LB.	MERIT NUMBER
No. 98	8 × 8 × 1	As rolled	201 000	32
No. 97	8 × 8 × 1	Pickled	146 000	4.8
No. 100	8 × 8 × 1	Pickled and stored 1 month	181 000	27.3
No. 101	8 × 8 × 1	As rolled	212 000	28.6
No. 102	8 × 8 × 1	Pickled	140 000	3.6
No. 105	8 × 8 × 1	Pickled and stored 1 month	187 900	33.1

It was by no means an infrequent occurrence for punched and pickled samples to give somewhat higher merit numbers than corresponding punched as rolled specimens. Possibly when no hydrogen embrittlement occurs, the effect of pickling may be beneficial through the tendency of the internal stresses in the cold-worked layer about the punched hole to be relieved by the solvent action of the pickling solution.

"Recovery" After Pickling:

That there is a recovery of ductility from the embrittlement caused in pickling with time is indicated in Table XXVI giving the results of angle bend tests of angles held one month and four days respectively after pickling before testing. Storing for the shorter period seems to be sufficient to give almost complete recovery of ductility.

Variations in Pickling Procedure:

Some data were obtained on the effect of varying the pickling temperature and also on the possible effect of heating at the ordinary pickling temperature (180° F., 83° C.) in water. Heating in water for 40 minutes had no appreciable aging or embrittling effect. Pickling in cold acid had a much smaller effect than pickling in hot acid; in fact, the effect in the case of the cold acid was barely perceptible, the embrittling effect of heating in hot acid also being very slight in these tests.

Cumulative Effects of Cold Working, Pickling and Galvanizing:

The embrittling effect of galvanizing in commercial structural steel is, as we have already seen, very slight, unless it is preceded by severe cold working, as in punching. This is true also of pickling. It may be pointed out that especially in the large punched angles, the angle bend and hole tension tests proved far more sensitive than the cold-worked impact test for detecting the embrittling effect of pickling and galvanizing. (Compare Fig. 6 with Fig. 12.) In the former types of test the material is apparently put into a borderline condition by the punching operation where, although it may still be quite ductile, it is on the verge of brittleness, so that the comparatively small effects of pickling or galvanizing may produce a very large change in behavior. In the cold-worked impact tests, however, such decided changes in behavior after pickling and galvanizing were rare, and it frequently occurred that the values after pickling and galvanizing were higher than before.

Heating in Galvanizing—Aging:

The extensive studies[1] which have recently been made upon aging and blue heat phenomena in iron and steel indicate embrittlement occurring in galvanizing to be due to the heating in galvanizing. The most widely held view is that the heating precipitates submicroscopic particles, previously held in supersaturated solution in the steel, of a critical size to cause brittleness. In some materials, as in malleable iron,[1] embrittlement may ensue upon heating to the blue heat region without any cold work, but in ordinary steel the all-important influence of prior cold work in producing an embrittling effect is now well recognized.[2] Presumably cold work aids in precipitating, segregating, or orienting the submicroscope particles causing brittleness so that their effect is a maximum. The embrittling effect of heating, as in galvanizing, on cold-worked mild steel such as is used for galvanized hardware has been well demonstrated by Allan and Geruso.[3]

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[1] S. Epstein and B. N. Daniloff, "Selected Bibliography on the Embrittlement of Structural Steel in Galvanizing," *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part I, p. 224 (1931).

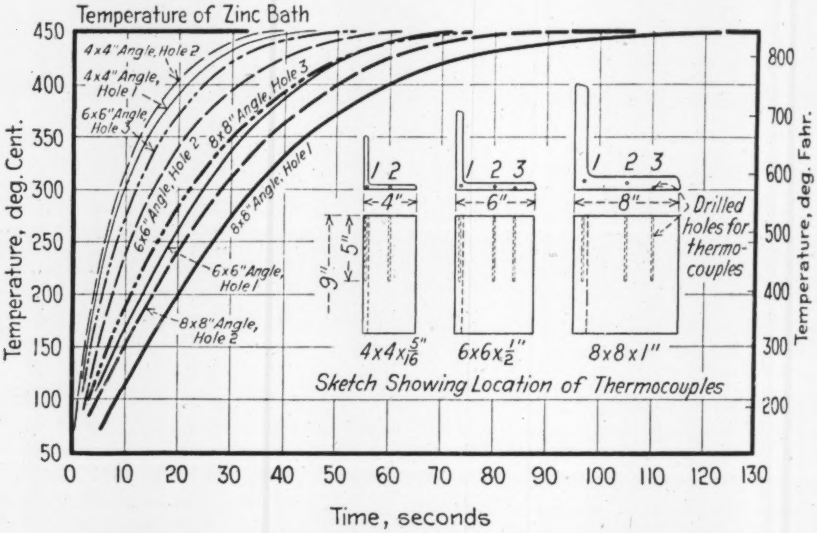

FIG. 19.—Heating Curves of Angles Immersed in Zinc Bath.

Rate of Heating in Galvanizing:

Depending to some extent on the severity of the prior cold work, heating to about 250° C. (480° F.) seems to cause the maximum embrittling effect.[4] Now since the galvanizing temperature is considerably higher than this, about 450° C. (840° F.), it was suggested that the angles during galvanizing may not reach the temperature of the zinc bath. Accordingly, the heating curves shown in Fig. 19 of angles immersed in the galvanizing bath were determined. As may be seen from the curves, after immersion in the zinc bath the rate of heating was so rapid that even the thickest portion of the biggest angle, 8 × 8 × 1 in., reached the temperature of the zinc bath in 2 minutes. Near the surface the temperature of the bath was reached in 75 seconds. An angle of this size is usually galvanized about 4 minutes. The thinner angles were completely heated through in a little over a minute (70 seconds) for the $6 \times 6 \times \frac{1}{2}$ in. angle, and in less than a minute (40 seconds) for the $4 \times 4 \times \frac{5}{16}$ in. angle, the surfaces of these angles being heated to temperature in still shorter times. These smaller sizes of angles are usually galvanized about three minutes. It is evident, therefore, that during a large proportion of the galvanizing period, the angles are at the temperature of the zinc bath, which is not the maximum embrittling temperature of heating after cold working, according to Bauer's cold-worked impact tests. Bauer, however, obtained his results, using a heating interval of one-half hour. It is possible that heating about 3 minutes at 840° F. (450° C.), as in galvanizing, produces a comparable amount of embrittlement to one-half hour's heating at 480° F. (250° C.). Precipitation hardening and softening by coalescence of the precipitated particles are known to take place simultaneously, the former being the faster reaction. Short-time heating should, therefore, favor maximum precipitation with minimum coalescence, while longer heating time may tend to lessen the hardening effects. Of course, even if the embrittling effect of the heating which occurs in galvanizing is not the maximum attainable, it may still be perceptible.

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[1] L. H. Marshall, "Embrittlement of Malleable Cast Iron Resulting from Heat Treatment," U. S Bureau of Standards *Technologic Paper No. 245*, Vol. 17, p. 677 (1923).

L. H. Marshall, "A Process for the Prevention of Embrittlement in Malleable Cast-Iron," *Preprint No. 1572-C*, Am. Inst. Mining and Metallurgical Engrs., 8 pp. (1926). Abstracted in *Mining and Metallurgy*, Vol. 7, p. 264 (1926).

[2] L. R. Van Wert, "Some Notes on Blue Brittleness," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Iron and Steel Division, Vol. 95, p. 230 (1931). Discussion, p. 238.

C. H. Desch, "The Age Hardening of Alloys," *Sibley Journal of Engineering*, Vol. 44, p. 65 (1932).

[3] J. C. Allan and R. L. Geruso, "Hot Galvanizing as It Affects Mild Steel," *Heat Treating and Forging*, Vol. 16, p. 70 (1930).

[4] O. Bauer, "Effect of Cold Work in Notch Brittleness," *Zeitschrift*, Bayerischen Revisions-Verein, Vol. 32, p. 15 (1928).

Possible Recrystallization During Galvanizing:

It has been suggested that the heating in galvanizing may cause coarse grain growth, such as is known to occur in low carbon steel on heating to about 600° C. (1200° F.) after a critical degree of cold work. The galvanizing temperature, however, is appreciably lower than the above, and the carbon content of structural steel is also higher than that at which the exaggerated grain growth phenomenon has been observed.[1] In Fig. 14, showing the cold-worked layer about the hole after galvanizing, no signs of grain growth are evident. Of course, submicroscopic recrystallization and reorientation of the crystal fragments deformed by cold work may occur during galvan-

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[1] A. Sauveur, "The Metallography and Heat Treatment of Iron and Steel," p. 265, McGraw-Hill Book Co., Inc., New York City (1916).

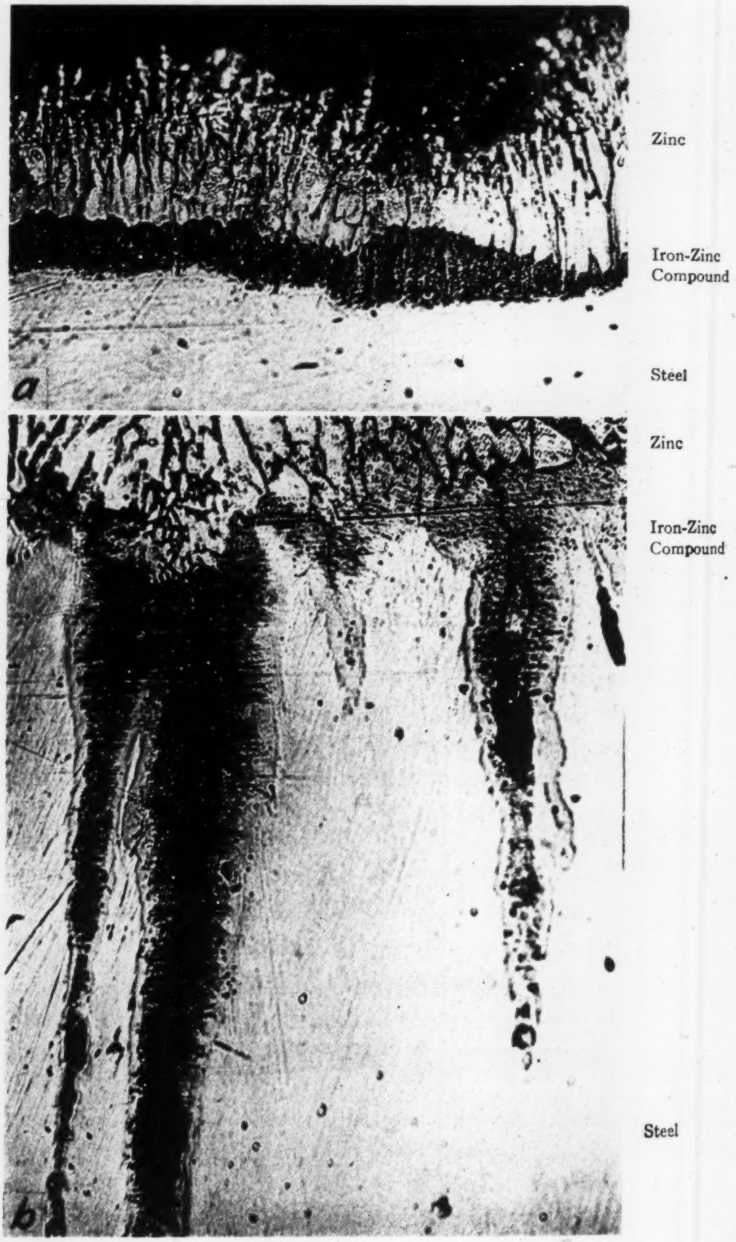
Zinc
Iron-Zinc Compound
Steel
a
Zinc
Iron-Zinc Compound
Steel
b

FIG. 20.—Contact Surface Between Zinc and Steel at Punched Hole in Galvanized Angle (× 500).

(*a*) Most of the path of contact is of this form showing no penetration.
(*b*) Sharp iron-zinc compound (stringers) penetrating into the steel.

izing,[1] but our understanding of the mechanism of aging and embrittlement is not far enough advanced at present to speak about this very definitely.

Zinc Penetration:

Another possible cause of embrittlement in galvanizing is the penetration of zinc into the steel, particularly at the crevices and tears about the punched hole. That such penetration may occur is illustrated in Fig. 20, showing a marked seeping in of the iron-zinc compound into fissures in the steel about a punched hole. Although even in a punched hole most of the contact surface between the zinc and steel is uniform without signs of irregular zinc penetration (Fig. 20(*a*)), occasionally rather deep penetration does occur, mostly along the longitudinal fibers. Since in testing and service the stresses are along the fibers and not transverse to them, the damaging effect of the longitudinal penetration is probably small.

TABLE XXVII.—RESULTS OF HOLE TENSION TESTS OF PUNCHED SPECIMENS HEATED TO GALVANIZING TEMPERATURE (450° C., 842° F.) IN LEAD AND IN ZINC.

The values are representative of 33 tests.

			Merit Number		
Laboratory	Kind of Steel	Size of Angle, in.	As Rolled	Heated in Zinc	Heated in Lead
No. 228	Duplex	6 × 6 × ½	28	13.8[a]	26.0[a]
				25.2[b]	21.8[b]
				23.0[a]	27.0[a]
				21.5[b]	27.5[b]
No. 463	Open hearth	6 × 6 × ½	30	26.4[a]	29.0[a]
				23.9[b]	26.4[b]
No. 44M	Open hearth	8 × 8 × ⅞	29.7	9.4[a]	5.6[a]
No. 45M	Open hearth	8 × 8 × ¾	28.2	3.8[a]	7.2[a]

[a] Pickled specimen.
[b] Not pickled.

Heating in Zinc and in Lead:

A very decisive means of showing whether the heating during galvanizing or the resulting zinc penetration is mainly responsible for embrittlement is afforded by heating in lead to the galvanizing temperature instead of in zinc. Lead does not wet the surface of steel and is known not to penetrate into or alloy with it. The hole tension tests in Table XXVII indicate that heating in lead had almost the same embrittling effect as heating in zinc and that where injurious embrittlement occurred in galvanizing it also occurred on heating similarly in lead. The conclusion may be drawn, therefore, that embrittlement in galvanizing is mainly due to the accompanying heating and only to a minor extent to the zinc penetration into or reaction with the steel.

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[1] G. R. Bolsover, "Brittleness in Mild Steel," *Journal*, Iron and Steel Inst., Vol. 119, p. 473 (1929).

M. A. Grossmann and C. C. Snyder, "Hardening by Reheating After Cold Working," *Transactions*, Am. Soc. Steel Treating, Vol. 13, p. 201 (1928).

C. TEMPERATURE OF TESTING

Effect of Notch:

In plain carbon steel a sharp drop in notched bar impact resistance takes place as the temperature of testing is reduced to below room temperature and very brittle behavior results. The courses of the impact resistance - temperature curves of several of the materials that were studied are shown in Fig. 21. This brittleness at zero or sub-zero temperature (depending on the steel) occurs, it may be noted, even in the absence of cold work, so that in this sense lowered temperature is a more potent embrittling factor than galvanizing, for example. For structural steel to become brittle at low temperatures, the presence of a fairly sharp notch, as in the notched-bar impact specimen, is essential. Unnotched bars do not show a sharp drop in impact resistance as the testing temperature is lowered and retain high ductility to temperatures as low as −80° C. (−112° F.).[1] In the angle bend test a drilled hole did not exert enough of a notch effect, even in the heaviest angles, to cause brittle behavior at temperatures as low as −40° C. (−40° F.).

Effect of Cold Work:

While low-temperature brittleness may occur in the absence of cold work, this factor is by no means without effect, as may be seen by examining Fig. 22. Cold work evidently causes the brittle region to extend to higher temperatures (in other words after cold work one does not need to go to so low a temperature before brittleness is encountered), this effect increases with the degree of deformation. After sufficient compression, 17 per cent in the case of the open-hearth steel, for instance, a close approach to brittleness occurred even at room temperature. With this degree of compression, the open-hearth steel was already brittle at 0° C. (32° F.) in the notched-bar impact test, whereas without cold work equally low values were obtained only at −40° C. (−40° F.).

Notch Effect of Punched Hole:

As the results of the hole tension and angle bend tests shown in Figs. 8 and 10 indicate, the cold work about the punched hole pro-

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[1] H. J. Gough and A. J. Murphy, "The Effect of Low Temperature on the Shock-Resisting Properties of New Wrought-Iron Chains," *Proceedings*, Inst. Mechanical Engrs., No. 5, p. 1159 (1930).

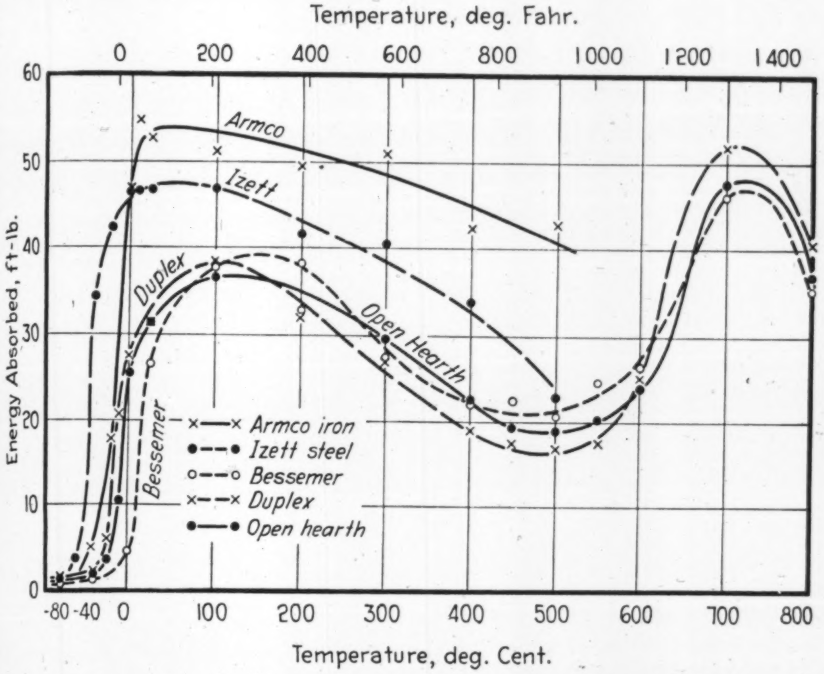

FIG. 21.—Change in Impact Resistance (Unworked, Notched Bars) with Temperature of Armco Iron and Bessemer, Duplex, Open Hearth and Izett Steels.

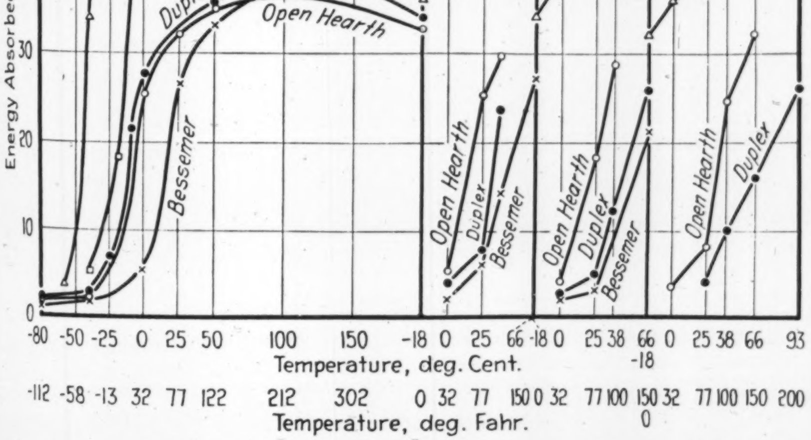

FIG. 22.—Effect of Lowered Temperature on Impact Resistance After Various Degrees of Cold Work by Compression.

vided the notch effect, lacking in the case of the drilled hole, which enabled the embrittling influence of lowered temperature to exert itself. After the foregoing, we can realize how an amount of cold work in punching, not sufficient to produce brittleness after galvanizing, when the specimens are tested at room temperature might produce brittleness at a slightly lower temperature, as actually occurred in the tests made.

Impact Resistance - Temperature Curve:

To return to Fig. 21, we may note that besides the brittle region at low temperature, there is a minimum in the impact resistance-temperature curve at about 500° C. (930° F.). The question was raised whether holding specimens at very low temperatures and at 450° C. (840° F.) would cause a lowering in impact values on subsequently testing at room temperature. Such tests indicated there was no lowering in impact resistance after holding at low temperatures, this being in conformity with other work.[1] In the open-hearth steel there was no lowering after holding at 450° C. (840° F.), but in the bessemer steel there was some lowering, this effect, however (since it was not exhibited by the open-hearth steel which had a minimum in the impact resistance - temperature curve at 450° C. (840° F.) equal to that in the bessemer steel), may not be directly related to the minimum in the impact resistance - temperature curve.

It will be recalled[2] that in angle bend and hole tension tests with drilled holes, crystalline fractures were obtained at low temperatures though accompanied by a high degree of prior deformation. This has also been noted by others.[3] The fact that a crystalline fracture, which has been described by Gough and Murphy as being due to a series of cleavages, each crossing several crystals with little change in direction, occurred at low temperatures even in the absence of a notch and after considerable prior deformation, indicates how great the tendency is for such cleavage to occur at low temperature. Such cleavage is characteristic of brittleness in the impact test and in the angle bend test, whenever brittleness occurred, and this fact may perhaps be emphasized in seeking to account for the course of the impact resistance - temperature curve.

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[1] See reference to work by Guillet and Cournot in paper by H. J. Gough and A. J. Murphy, "The Effect of Low Temperature on the Shock-Resisting Properties of New Wrought-Iron Chains," *Proceedings*, Inst. Mechanical Engrs., No. 5, p. 1159 (1930).

[2] See p. 306.

[3] H. J. Gough and A. J. Murphy, "The Effect of Low Temperature on the Shock-Resisting Properties of New Wrought-Iron Chains," *Proceedings*, Inst. Mechanical Engrs., No. 5, p. 1159 (1930).

Discussion of Fractures:

It may be assumed that under certain notch or stress concentration conditions (including cold work), and at lower temperatures, the tendency for iron is to cleave along certain crystal planes producing the characteristic crystalline fracture associated with low impact resistance. As the temperature increases somewhat, in the region of room temperature to 100° C. (212° F.) (depending on the steel), the effect of the notch becomes "dulled" and is not sufficient to cause cleavage on the crystal planes in question; plastic deformation takes place instead, probably on another set of crystal planes, giving the well known silky, drawn-out fracture, and high impact resistance. As the temperature increases further (see Fig. 21) the degree of deformation decreases for some unknown reason, possibly connected with the blue heat phenomena in iron, so that the minimum at 450 to 500° C. (840 to 930° F.) occurs. That this minimum may not be wholly connected with the speed of testing and rapid work-hardening at that temperature, as is generally held, following the views of Fettweiss,[1] is indicated by the fact that even at the slow speed of testing in an ordinary tension test (without a notch) there is also a minimum in ductility at this temperature region, as has recently been pointed out.[2]

Going to still higher temperatures (600 to 700° C., 315 to 370° F.), another rapid rise in impact resistance sets in, possibly denoting another change in the type of deformation on perhaps another set of crystal planes. The other effect of rising temperature, however, already noted, of "dulling" the notch may also play an important part here. At this relatively high temperature the steel is rapidly decreasing in hardness, so that it is considerably softer than at room temperature, and the effect of the notch in restricting deformation to the metal at the bottom of the notch must be very small. Thus a possible change in the mode of deformation and the weakening of the effect of the notch may account for the high impact resistance in this temperature range. The falling off in impact resistance at still higher temperatures (800° C., 1470° F.) is certainly not due to a lack of ductility but to the extreme softness, so that under the blow of the hammer, the specimen bends over without absorbing much energy, as has been suggested by Quick.[2]

Figure 23 indicates these changes in the appearance of the fractures along the course of the impact resistance - temperature curve of

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[1] F. Fettweiss, "Blue Brittleness and Aging of Steel," *Stahl und Eisen*, Vol. 39, p. 1 (1919).

[2] G. W. Quick, "Tensile Properties of Rail Steels at Elevated Temperatures," U. S. Bureau of Standards *Journal of Research*, Vol. 8, p. 173 (1932).

Fig. 21 in the bessemer steel samples. Identical fractures were obtained with the open-hearth steel, except that whereas in the bessemer steel a crystalline "cleavage" fracture occurred at 0° C. (32° F.), it did not occur in the open-hearth steel until the temperature was lowered to $-25°$ C. ($-13°$ F.).

The question of fracture has been gone into at some length, because of its interest in regard to the mechanism of injurious embrittlement. Thompson and Millington[1] early suggested that precipitation effects, such as are now regarded to occur on reheating after cold work might cause an undue tendency for deformation to ensue on certain cleavage planes and thus produce brittle fracture. It is rather difficult to test this hypothesis experimentally. It might be assumed, however, that, if cleavage occurred on a certain set of crystal planes, these planes would be exposed at the surface of a crystalline fracture, whereas another set of planes would be exposed at the surface of a silky fracture. This is not readily determinable by X-rays, because they penetrate rather deeply beneath the surface, but some indications might be obtained using softer radiation from copper, for example. The similar electron diffraction method, much less penetrating than the X-ray, is being perfected and might be

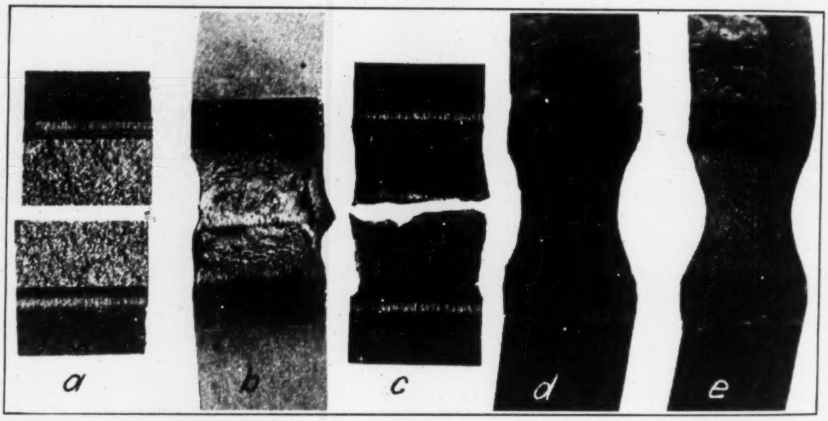

FIG. 23.—Effect of the Temperature of Testing on the Appearance of Charpy Impact Test Fractures of Bessemer Steel. (Compare with curves in Fig. 21.)

(*a*) Crystalline fracture. Tested at 0° C. (32° F.).
(*b*) Silky fracture. Tested at 100° C. (212° F.).
(*c*) Fibrous with lesser amount of deformation. Tested at 500° C. (930° F.).
Note that this specimen broke in two as did (*a*), but not (*b*), (*d*) or (*e*).
(*d*) Ductile showing fracture at bottom of notch. Tested at 700° C. (1290° F.).
(*e*) Ductile, with no fracture; specimen merely bent over. Tested at 800° C. (1470° F.).

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[1] F. C. Thompson and W. E. W. Millington, "The Plastic Deformation of Alpha- and Gamma-Iron," *Journal*, Iron and Steel Inst., Vol. 109, p. 67 (1924).

applicable.[1] Tammann[2] has recently described numerous metallographic methods for determining the orientation of crystallites, some of which might prove useful. The fractures shown in Fig. 23 (*a*), (*b*) and (*c*) should prove especially interesting for studies by these methods. The type illustrated by Fig. 23(*c*), occurring at 450 to 500° C. (840 to 930° F.) would probably prove the most difficult, because of the oxidation at the surface, but means are, of course, available for preventing oxidation.

D. STEEL

We cannot deal with embrittlement without discussing the steel. The really remarkable differences between steels of almost the same composition in their response to such embrittling factors as cold work and low temperatures, for example, have been apparent from the data already given (Figs. 12, 21, and 22). Table XXVIII gives the results of chemical analyses, tension tests, angle bend, and hole tension tests of representative steels used in this investigation. (A complete table of the above data for every heat of steel used in this study is available and can be supplied on request.) These data show plainly that steels which proved brittle in the angle bend and hole tension tests gave high ductility in the ordinary tension test.

Soundness, Homogeneity, and Grain Size:

Despite the great amount of material studied, no evidences of such gross defects as undue segregation or porosity were encountered. and all of the steel appeared to be of uniformly good quality on this respect. Hole tension tests of specimens machined from the heel and toe of angles, showed that although the steel at the heel tended to have somewhat lower ductility, still there were no great differences between the heel and toe in susceptibility to embrittlement. In general, the grain size appeared somewhat larger at the heel than at the toe, although the grain at the heel of the angle which failed in erection (Fig. 24) appeared exceptionally coarse.

Semi-Killed and Killed Steel:

The usual structural steel is semi-killed. Little or no silicon is added in the furnace or ladle, and although it contains too much carbon and other deoxidizers to effervesce in the molds, it is not a completely killed steel. It was suggested that perhaps killed steel of structural composition might be less susceptible to embrittlement than ordinary semi-killed structural steel. The data in Table XXIX

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[1] J. J. Thompson, "Electron Optics," *Nature*, Vol. 129, p. 81 (1932).

[2] G. Tammann, "The Determination of Crystallite Orientation," *Journal*, Inst. Metals, Vol. 44, p. 29 (1930).

TABLE XXVIII.—RESULTS OF CHEMICAL ANALYSES, TENSION TESTS, ANGLE BEND, AND HOLE TENSION TESTS OF REPRESENTATIVE STEELS STUDIED.

Chemical analyses and tensile properties submitted by the mills.

Laboratory[a]	Size of Angle, in.	Chemical Analysis, per cent				Tensile Properties				Punched Galvanized Tested at 25° C. (77° F.)										
										Angle Bend Test						Hole Tension Test				
											Merit Number[b]						Merit Number[b]			
		Copper	Manganese	Phosphorus	Sulfur	Yield Point, lb. per sq. in.	Ultimate Strength, lb. per sq. in.	Elongation, in 8 in., per cent	Reduction of Area, per cent	Average Maximum Load, lb.	Col. 1	Col. 2	Col. 3	Col. 4	Number of Tests	Average Maximum Load, lb.	Col. 1	Col. 2	Col. 3	Col. 4	Number of Tests
BESSEMER STEEL[c]																				
No. 128	8 × 8 × 1	0.08	0.47	0.102	0.035	44 640	66 760	28.5	....	96 500	2.0	3.0	3.0	...	3	73 800	0	....	....	....	1
No. 148	6 × 6 × ½	0.08	0.47	0.102	0.035	40 670	66 140	26.0	....	40 200	0	1.0	2.0	2.0	5	26 400	1.0	....	....	....	1
No. 392	6 × 6 × ½	0.15	0 43	0.092	0.039	40 580	73 640	25.6	....	47 200	0	2.0	2.0	3.0	6	34 500	0	....	....	....	1
DUPLEX STEEL[d]																				
No. 108	8 × 8 × 1	0.22	0.54	0.017	0.030	38 550	65 940	26.2	....	103 500	4.0	6.0	9.0	....	3	81 800	5.0	....	....	....	1
No. 201	6 × 6 × ½	0.22	0.54	0.017	0.030	37 120	63 480	27.7	....	56 650	14.0	20.0	26.0	30.0	9	41 670	14.0	24.0	28.0	29.0	4
No. 37M	6 × 6 × ½	0.20	0.48	0.015	0.026	39 050	64 440	27.5	53.0	60 800	24.0	....	....	....	1	43 100	20.0	24.0	32.0	33.0	5
No. 225	6 × 6 × ½	0.20	0.44	0.012	0.032	37 070	62 940	27.7	....	55 060	8.0	11.0	16.0	23.0	4	38 500	4.7	15.8	23.0	23.0	4
OPEN-HEARTH STEEL[e]																				
No. 73	8 × 8 × 1	0.21	0.37	0.008	0.036	36 450	59 400	27.5	....	96 000	4.0	13.0	33.0	37.0	6	....	....	....	....	....	..
No. 41M	8 × 8 × $\frac{7}{8}$	0.21	0.54	0.015	0.037	36 280	61 740	28.5	48.0	119 000	4.0	5.0	9.0	12.5	7	91 500	1.0	....	....	....	1
No. 150M	8 × 8 × ¾	0.15	0.61	0.010	0.036	41 100	60 840	30.0	59.5	100 400	18.9	20.0	25.0	25.5	4	....	....	....	....	....	..
No. 134M	6 × 6 × 1	0.21	0.43	0.009	0.029	38 070	61 130	29.6	58.3	96 200	0.8	1.9	2.6	2.9	4	....	....	....	....	....	..
No. 153M	6 × 4 × $\frac{7}{8}$	0.15	0.62	0.012	0.044	45 190	64 700	31.2	58.0	83 000	2.0	3.2	13.1	15.1	6	....	....	....	....	....	..
No. 115M	6 × 6 × ¾	0.18	0.46	0.020	0.041	35 430	60 430	32.5	....	79 200	2.1	2.5	23.0	23.5	4	53 900	17.5	....	....	....	1
No. 454	6 × 6 × ½	0.19	0.47	0.011	0.027	34 910	58 190	29.0	....	56 000	27.0	30.0	36.6	44.0	14	39 200	26.0	30.0	34.0	39.0	5
No. S-21	6 × 6 × ½	0.18	0.32	0.015	0.035	37 430	58 200	29.5	57.3	64 900	18.6	24.0	28.8	31.0	10	....	....	....	....	....	..

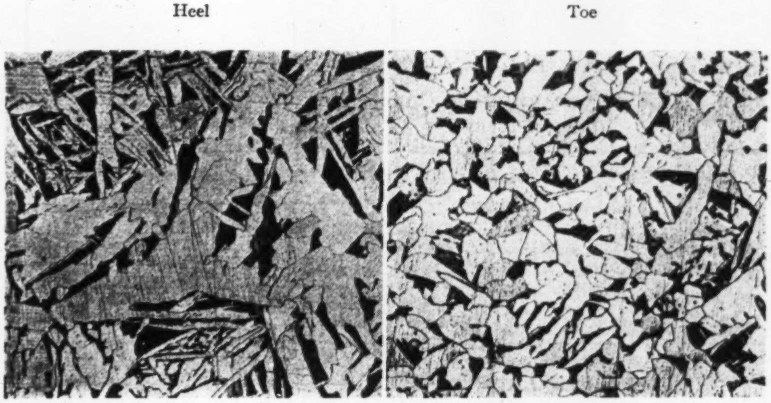
[a] Each laboratory number represents a different heat of steel, except where two laboratory numbers are connected by braces indicating that more than one size angle was rolled from the same heat.

[b] The merit number is the sum of the percentage elongation in 2 in. and the percentage reduction in thickness.
Where less than 5 tests were made the merit number of each test is given individually.
Where 5 or more tests were made, the merit number in Column 1 gives the lowest value; column 2 the average of the lower half; column 3 the average of the upper half, and column 4 the highest value.

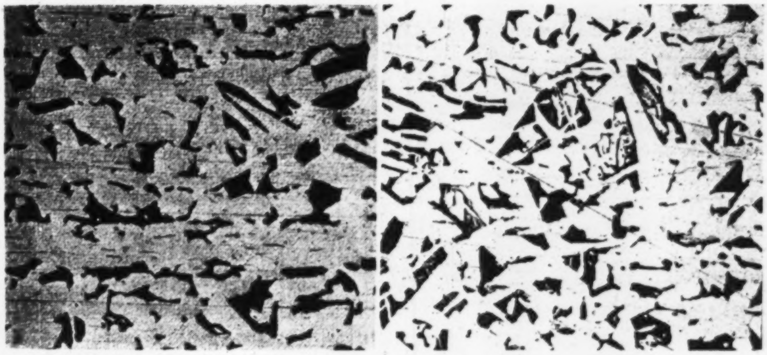
[c] Representatives of 9 heats of bessemer steels studied.

[d] Representatives of 24 heats of duplex steels studied.

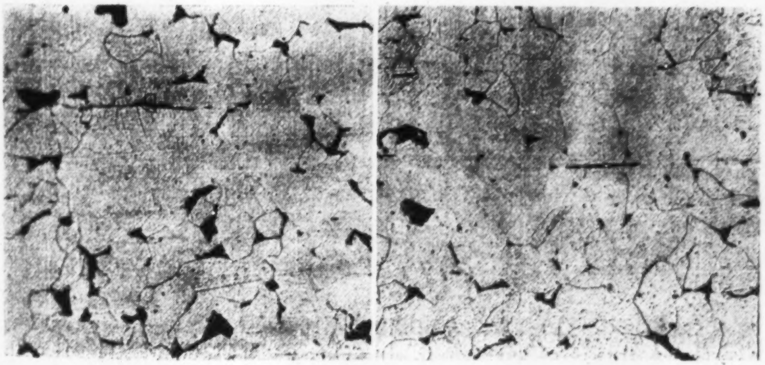
[e] Representatives of 101 heats of open-hearth steels studied.



(a) 8 × 8 × $\frac{15}{16}$ in. duplex angle which failed in erection.



(b) 8 × 8 × 1 in. open-hearth angle.



(c) 8 × 8 × 1 in. bessemer angle.

FIG. 24.—Grain Size in Heel and Toe of Angles (× 100).

indicate that there was some, though not very great, superiority in impact resistance after cold work of the killed open-hearth steel over

TABLE XXIX.—COMPARISON OF CHARPY IMPACT TEST RESULTS OF SPECIMENS FROM DIFFERENT THICKNESSES OF SECTIONS.

Degree of Compression, per cent	Condition	Energy Absorbed, ft-lb.					
		"Semi-Killed" Open-Hearth Steel Tested at 25° C. (77° F.)		Killed Open-Hearth Steel[a] Tested at 25° C. (77° F.)		Izett Steel Tested at 0° C. (32° F.)	
		$8 \times 8 \times 1$ in. Angle	$6 \times 6 \times \frac{1}{2}$ in. Angle	$8 \times 8 \times 1$ in. Angle	$6 \times 6 \times \frac{1}{2}$ in. Angle	1-in. Plate	$\frac{13}{32}$-in. Plate
Not worked	As rolled	28.3	28.4	32.8	35.4	....	46.0
5	As rolled	12.5	25.2	26.7	35.3	27.4	44.1
5	Galvanized	....	24.7	25.6	28.3	....	....
9	As rolled	5.3	12.8	22.4	32.6	25.5	39.7
9	Galvanized	....	12.8	6.8	21.7	....	....
17	As rolled	4.6	6.6	11.7	27.2	22.0	34.5
17	Galvanized	....	6.6	9.3	18.3	....	....

[a] Chemical Composition, per cent: Carbon, 0.20; Manganese, 0.54; Phosphorus, 0.020; Sulfur, 0.033; Silicon 0.11; Aluminum, 0.003.

TABLE XXX.—RESULTS OF ANGLE BEND TESTS OF STRUCTURAL SILICON STEEL.

$6 \times 6 \times \frac{5}{8}$ in. angles.[a]

Laboratory	Kind of Hole	Size of Hole, in.	Edge Distance, in.	Edge Material, in.	Condition	Merit Number
No. 597-1	Punched	$\frac{13}{16}$	1	$\frac{19}{32}$	Rolled	16.7
No. 597-2	Punched	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	Rolled	19
No. 598-1	Punched	$\frac{13}{16}$	1	$\frac{19}{32}$	Galvanized	5.1
No. 598-2	Punched	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	Galvanized	9.4
No. 595-1	Punched	$\frac{13}{16}$	1	$\frac{19}{32}$	Galvanized	11.4
No. 595-2	Punched	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	Galvanized	7.8
No. 596-1	Punched	$\frac{13}{16}$	1	$\frac{19}{32}$	Galvanized	11.5
No. 596-2	Punched	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	Galvanized	7.6
No. 599-2	Drilled	$\frac{15}{16}$	$1\frac{1}{4}$	$\frac{25}{32}$	Galvanized	24.5

[a] Chemical Composition:

LABORATORY	CARBON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT
No. 597-1	0.36	0.54	0.29
No. 596-2	0.35	0.80	0.24
No. 599-2	0.37	0.56	0.24

the semi-killed. In a few angle bend tests the values were not higher than those obtained with semi-killed steel. However, tests were made of only one large size angle (these tests showed good ductility) which, of course, is insufficient to determine whether large killed angles have the same marked susceptibility to embrittlement as large semi-killed angles.

Structural Silicon Steel:

A few tests were made of medium size angles of structural silicon steel conforming to A.S.T.M. Specifications A 94 - 29,[1] which is a commercial killed steel. As shown in Table XXX after punching and galvanizing these showed injurious embrittlement, no doubt due to the comparatively large amounts of hardening elements—carbon silicon, and manganese—present. After drilling, however, good ductility was obtained.

Amount of Reduction in Rolling:

That the greater severity of the punching operation in the larger angles does not wholly account for their brittle behavior is indicated by the impact test results in Table XXIX, which show that the impact resistance of specimens from thicker angles were more greatly reduced by cold work than those from thinner angles. This may be due to the smaller reduction the large angles receive in rolling and the resulting slightly larger grain. It is suggested that the use of larger ingots for the heavier sections offers a field for profitable study.

TABLE XXXI.—RESULTS OF IMPACT TESTS OF COMPRESSED SPECIMENS OF OPEN-HEARTH AND DUPLEX STEEL.

Specimens from 4 × 4 × ½ in. angles.

		ENERGY ABSORBED, FT-LB.			
LABORATORY	KIND OF STEEL	NOT WORKED	COMPRESSED 5 PER CENT	COMPRESSED 9 PER CENT	COMPRESSED 17 PER CENT
No. 119M	Duplex	34.8	31.9	23.6	9.3
No. 121M	Open hearth	44.6	38.9	34.8	23.4
No. 124M	Duplex	46.4	36.6	31.4	8.7

Grain Size—Normality and Abnormality:

In view of the probable effect of fine grain in reducing the susceptibility to embrittlement, it is of interest to note that there were marked variations in the steels studied in the normality after carburizing (eight hours in a commercial carburizer at 1700° F., 925° C.), some being very normal with large grain and some abnormal with fine grain, as illustrated in Fig. 25. Abnormal specimens showed slightly higher impact resistance after cold working.

Duplex Steel:

Several of the duplex heats were abnormal, and the differences in this respect possibly accounted in part for the variations in results obtained among the duplex heats studied. Impact tests in which specimens from duplex heats gave lower values than those from open-hearth steel, but yet not as low as those shown in Fig. 12, are given in Table XXXI. Other differences that may account for variations in the quality of duplex steel are the percentage of bessemer blown metal used and the time and manner of blowing the bessemer steel.[1]

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[1] 1930 Book of A.S.T.M. Standards, Part I, p. 80 (1930).

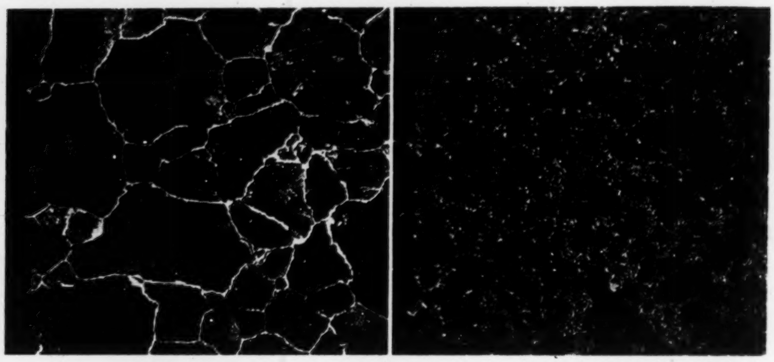
(*a*) Normal. (*b*) Abnormal.

FIG. 25.—Structure After Carburizing of Representative Normal and Abnormal 6 × 6 × ½ in. Open-Hearth Angles (× 100).

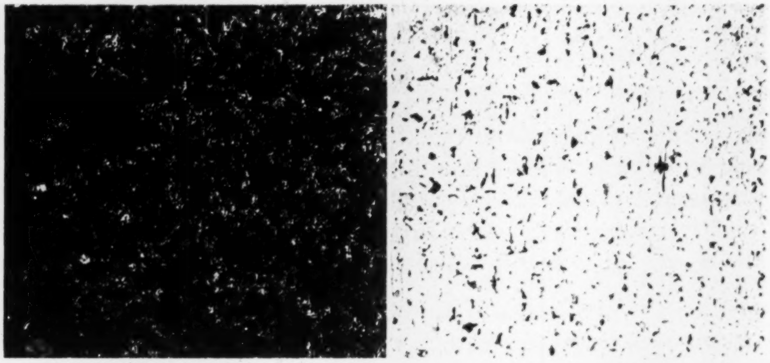
(*a*) Carburized layer. (*b*) As received.

FIG. 26.—Structure of Izett Steel Before and After Carburizing (× 100).

While the number of specimens and heats of duplex steel represented in this study was much smaller than in the case of open-hearth steel the general tendency has been for the duplex steel to show a somewhat greater susceptibility to embrittlement. Thus in duplex steel the impact resistance after cold working decreased more rapidly and the average merit number in the angle bend test, especially at lowered testing temperatures, was lower. However, there was an overlapping of results, so that in individual instances duplex angles gave higher values in the angle bend test than open-hearth angles. It should be noted that for structural uses where excessive cold work plays no part, the results of this study give no indication of differences between open-hearth and duplex steel.

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[1] Discussion by G. B. Waterhouse of paper by R. T. McCaffery, "The Bessemer Process and Its Product," *Year Book*, Am. Iron and Steel Inst., p. 378 (1931).

TABLE XXXII.—RESULTS OF HOLE TENSION TESTS OF IZETT STEEL.[a]

Laboratory	Plate Size, in.	Hole	Condition	Testing Temperature		Maximum Load, lb.	Merit Number
				deg. Cent.	deg. Fahr.		
No. 343-1	$\frac{13}{32}$	Punched	Rolled	25	77	33 800	46
No. 343-2	$\frac{13}{32}$	Punched	Galvanized	25	77	32 500	36
No. 343-3	$\frac{13}{32}$	Drilled	Rolled	25	77	33 650	78
No. 343-4	$\frac{13}{32}$	Drilled	Galvanized	25	77	34 500	63
No. 343-5	$\frac{13}{32}$	Punched	Galvanized	−40	−40	35 600	42
No. 343-6	$\frac{13}{32}$	Drilled	Galvanized	−40	−40	40 100	60
No. 344-1	1	Punched	Rolled	25	77	103 100	30
No. 344-2	1	Punched	Galvanized	25	77	107 900	28
No. 344-3	1	Drilled	Rolled	25	77	111 300	78
No. 344-4	1	Drilled	Galvanized	25	77	118 100	63
No. 344-5	1	Punched	Galvanized	−40	−40	95 300	11
No. 344-6	1	Drilled	Galvanized	−40	−40	123 000	49

[a] Chemical Composition:

PLATE SIZE, IN.	CARBON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT	ALUMINUM, PER CENT	NITROGEN, PER CENT
$\frac{13}{32}$	0.13	0.58	0.04	0.05	0.07
1	0.07	0.54	0.04	0.05	0.07

Izett Steel:

The outstandingly high properties of the Izett steel examined, after cold working and at low temperatures, can hardly have escaped notice in the data previously reported (see Figs. 12, 21, and 22). This steel is a plain carbon, not an alloy, structural steel which has been developed by the F. Krupp Co. in Germany in the search for a boiler steel that would not undergo caustic embrittlement.[1] It contains relatively little silicon (0.04 per cent) but an appreciable amount of aluminum (0.05 per cent) and is presumably a killed steel. Its low susceptibility to embrittlement, however, is probably not to be attributed solely to the content of aluminum but rather to the manner of deoxidation in manufacture, details of which have not been disclosed.[1] Undoubtedly significant is the fact that Izett has a fine grain and is decidedly abnormal after carburizing, as indicated in Fig. 26.

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[1] S. W. Parr and F. G. Straub, "Embrittlement of Boiler Plate," *Bulletin No. 117*, University of Illinois Engineering Experiment Station, Urbana, Ill. (1928); also F. G. Straub, "Embrittlement of Boilers," *Bulletin No. 216*, University of Illinois Engineering Experiment Station, Urbana, Ill. (1931).

Izett steel was not available in the form of angles, but hole tension tests of $\frac{13}{32}$-in. and 1-in. plate (Table XXXII) indicated that after punching and galvanizing in these tests, as after cold working in impact tests, its susceptibility to embrittlement was much lower than that of ordinary open-hearth structural steel. Thus the $\frac{13}{32}$ in. punched and galvanized plate still gave high ductility at $-40°$ C. ($-40°$ F.), whereas all the punched and galvanized open-hearth steel samples of this size were already brittle at $-25°$ C. ($-13°$ F.). Punched Izett steel, however, is not entirely immune to embrittlement, as is indicated by the fairly low value, only a little above a merit number of 10, which was obtained at $-40°$ C. ($-40°$ F.) in the 1-in. plate.

Izett, so far as is known, is not commercially manufactured in this country, and it is still apparently in a stage of development in Germany. It has been rumored that immunity from embrittlement is not obtained in every heat made but that the percentage of unsuccessful or "off" heats is high, though Neuendorff's[2] recent discussion would indicate that it has recently been made of quite uniform quality. Izett, therefore, can hardly be considered as an immediately practicable solution of the engineering problem of embrittlement, but its properties, as indicated by the tests made in this study, appear to be so favorable as to show great promise. If the Izett type of steel can be made regularly in commercial production, it would appear to be possible to punch and galvanize such angles in the larger sizes without fear of injurious embrittlement.

Mechanism of Embrittlement in Steel:

Coming to the uncertain ground of the causes of embrittlement (which is now generally held to be due in part, as has been stated, to precipitation effects of impurities in the steel) cold working and reheating produce or at least favor precipitation, although how the hardening and embrittlement take place has by no means been cleared up.[3] There is even more uncertainty as to what impurity or compound is the cause of the precipitation effects. Carbon,[1] oxygen,[2] nitrogen,[3] and phosphorus,[4] all present in steel and all subject to precipitation effects, have been blamed, but since no steel is free from these elements it is difficult to separate the individual effects of any of them. It is likely that in a steel precipitation and embrittlement are caused by mutual changes in solubility, the presence of one of these elements having a large effect on the solubilities of the others. The only way to settle the question would be to make up and study alloys of pure iron with the various impurities varying one at a time, but this is extremely difficult to accomplish because it is well nigh impossible to prepare iron free from oxygen, carbon, and nitrogen. In this engineering study, therefore, it was necessary to make the best of the evidence afforded by the examination of commercial or other available material, admittedly unsatisfactory as that evidence is.

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[1] G. Neuendorff, "Izett Steel, What It Is and What It Is Used For," *Metals and Alloys*, Vol. 3, p. 61 (1932); see also A. Fry, U. S. Patent No. 1, 729,378, September 24, 1929, and F. Giolitti, "Strength of Deformed and Aged Steel," *Metal Progress*, Vol. 20, No. 1, p. 87 (1931).

[2] G. Neuendorff, "Izett Steel, What It Is and What It Is Used For," *Metals and Alloys*, Vol. 3, p. 61 (1932).

[3] L. R. Van Wert, "Some Notes on Blue Brittleness," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Iron and Steel Division, Vol. 95, p. 230 (1931). Discussion, p. 238.

Effect of Arsenic, Tin, Chromium and Copper:

Analyses were made of the materials studied for phosphorus and silicon and for several elements not ordinarily determined. The small amounts of arsenic[5] (nil to 0.015 per cent), tin[6] (0.003 per cent) and chromium (nil to 0.05 per cent) found apparently had no effect on embrittlement, nor did the unusually small amounts of copper[7] (nil to 0.05 per cent). Copper-bearing structural steel angles conforming to A.S.T.M. Specifications A 7 – 29[8] were not available for study. The data in the references cited,[7] however, indicating that a copper content under 0.5 per cent has no appreciable embrittling effect and a statement from a large steel producer that the copper content of structural steel (about 0.25 per cent) would certainly not be expected to influence the susceptibility to embrittlement in punching and galvanizing, would appear to justify classing copper-bearing structural steel together with ordinary structural steel in respect to propensity toward embrittlement.

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[1] A. A. Bates, "Aging in Low-Carbon Steels," *Transactions*, Am. Soc. Steel Treating, Vol. 19, p. 449 (1932).

[2] H. W. Gillett, "The Unknown Influence of Oxygen and Nitrogen on the Iron-Carbon System," *Metals and Alloys*, Vol. 1, p. 237 (1929).

[3] W. Köster, "Nitrogen in Technical Iron," *Archiv für das Eisenhüttenwesen*, Vol. 3, p. 637 (1930).

[4] W. Köster, "Precipitation Hardening in Iron-Phosphorus Alloys," *Archiv für das Eisenhüttenwesen*, Vol. 4, p. 609 (1931).

[5] A. E. Cameron and G. B. Waterhouse, "The Effects of Arsenic on Steel," *Journal*, Iron and Steel Inst., Vol. 113, p. 355 (1926).

O. Bauer, "Arsenic in Ingot Steel," *Mitteilungen* der Deutschen Materialprüfungsanstalt, Sonderheft 13, p. 58 (1930).

[6] J. H. Whiteley and A. Braithwaite, "Some Observations on the Effect of Small Quantities of Tin in Steel," *Journal*, Iron and Steel Inst., Vol. 107, p. 161 (1923).

[7] F. Nehl, "Mechanical Properties of Copper Steels as Affected by Heat Treatment," *Stahl und Eisen*, Vol. 50, p. 678 (1930).

H. Buckholtz and W. Köster, "On the Temper Hardening of Copper Steels," *Stahl und Eisen*, Vol. 50, p. 687 (1930).

[8] 1930 Book of A.S.T.M. Standards, Part I, p. 67 (1930).

Effect of Carbon, Phosphorus, Nitrogen, and Oxygen:

As for the effects of carbon, phosphorus, nitrogen, and oxygen, this can better be judged from Table XXXIII. Here we can see that arranging the particular samples tested in the order of their susceptibility to embrittlement—bessemer, duplex, and open-hearth—arranges them also in the order of their nitrogen and phosphorus content, but not in the order of their oxygen content; for example, the oxygen was higher in the last open-hearth steel than even in the bessemer steel. The carbon content is evidently not directly involved, since there was an equal amount of carbon in the duplex and open-hearth steel, and all of the steels had much more than the very small amount

TABLE XXXIII.—RELATION BETWEEN CONTENT OF NITROGEN, PHOSPHORUS, AND OXYGEN AND SUSCEPTIBILITY TO EMBRITTLEMENT AFTER COLD WORK.

Laboratory	Kind of Steel	Nitrogen, per cent	Phosphorus, per cent	Oxygen, per cent[a]	Energy Absorbed in Charpy Impact Tests, ft-lb.			
					Not Worked	Compressed 5 per cent	Compressed 9 per cent	Compressed 17 per cent
No. 189..	Bessemer........	0.012	0.099	0.015	26.5	3.4	2.2	2.3
No. 212..	Duplex..........	0.008	0.018	0.007	31.5	7.8	4.8	4.0
No. 272..	Open hearth.....	0.003	0.009	0.020	30.0	....	8.5	5.5
No. 292..	Open hearth.....	0.003	0.008	0.008	28.4	25.2	17.7	8.0

[a] Oxygen determined by the vacuum fusion method.

TABLE XXXIV.—RESULTS OF HOLE TENSION TESTS OF REPHOSPHORIZED OPEN-HEARTH SHEET BAR AND NITROGENIZED OPEN-HEARTH SHEET BAR.

Punched Holes.[a]

Laboratory	Material	Plate Size, in.	Condition	Maximum Load, lb.	Merit Number
No. 559-1....	Rephosphorized open-hearth sheet bar................	$\frac{1}{2}$	As rolled....	43 000	37.9
No. 559-3....	Rephosphorized open-hearth sheet bar................	$\frac{1}{2}$	Galvanized .	33 800	30.7
No. 579-13...	Nitrogenized open-hearth sheet bar (0.017 per cent N_2)	$\frac{3}{8}$	As rolled....	29 600	60.0
No. 579-14...	Nitrogenized open-hearth sheet bar (0.017 per cent N_2)	$\frac{3}{8}$	Galvanized .	27 500	48.0
No. 587-13...	Nitrogenized open-hearth sheet bar (0.008 per cent N_2)	$\frac{3}{8}$	As rolled....	27 300	66.0
No. 587-14...	Nitrogenized open-hearth sheet bar (0.008 per cent N_2)	$\frac{3}{8}$	Galvanized .	27 500	54.0

		Composition, per cent		
		Carbon	Phosphorus	Nitrogen
No. 559......	Rephosphorized open-hearth sheet bar................	0.12	0.105	0.003
No. 579......	Nitrogenized open-hearth sheet bar....................	0.06	0.009	0.017
No. 587......	Nitrogenized open-hearth sheet bar....................	0.06	0.009	0.008

[a] The nitrogenized open-hearth sheet bar was prepared and supplied by the Inland Steel Co.

of carbon necessary to give maximum precipitation hardening and embrittlement. The data in Table XXXIII, while by no means determinative, point more strongly to nitrogen than to oxygen as responsible for embrittlement. The difficulty with the oxygen content, however, is that it represents all the oxygen, that insoluble in the steel as well as soluble, whereas only the soluble oxygen would be expected to play much part in precipitation effects.

Another rather indirect indication that nitrogen is concerned with embrittlement is the fact that in bessemer steel (0.012 per cent nitrogen) strain lines after punching the hole were revealed very prominently by etching with Fry's reagent, whereas in duplex steel (0.008 per cent nitrogen) these lines were very faint, and in open-hearth steel (0.004 per cent nitrogen) they could not be revealed at all (Fig. 27). Steels in which strain lines can be revealed in this way have been considered more susceptible to embrittlement.[1] Evidence has recently been adduced to indicate that nitrogen in steel markedly influences its ability to show strain lines upon etching with Fry's reagent.[2]

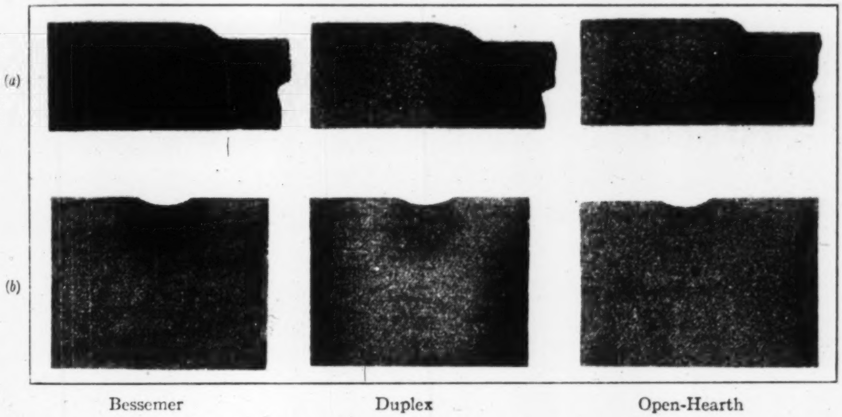

FIG. 27.—Appearance of Cold-Worked Bessemer, Duplex, and Open-Hearth Steel Specimens After Etching with Fry's Micro-Reagent. Strain lines were revealed prominently in the bessemer steel, only faintly in the duplex, and not at all in the open-hearth steel.

(a) Impact specimens, compressed 17 per cent.
(b) Specimens indented in a Brinell machine.

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[1] H. Jungbluth, "Aging Notch-Toughness and the Etching of Stress Figures," *Archiv für das Eisenhüttenwesen*, Vol. 4, p. 533 (1931).

[2] C. W. MacGregor and F. R. Hensel, "The Influence of Nitrogen in Mild Steel on the Ability of Developing Flow Layers," *Journal of Rheology*, Vol. 3, p. 37 (1932).

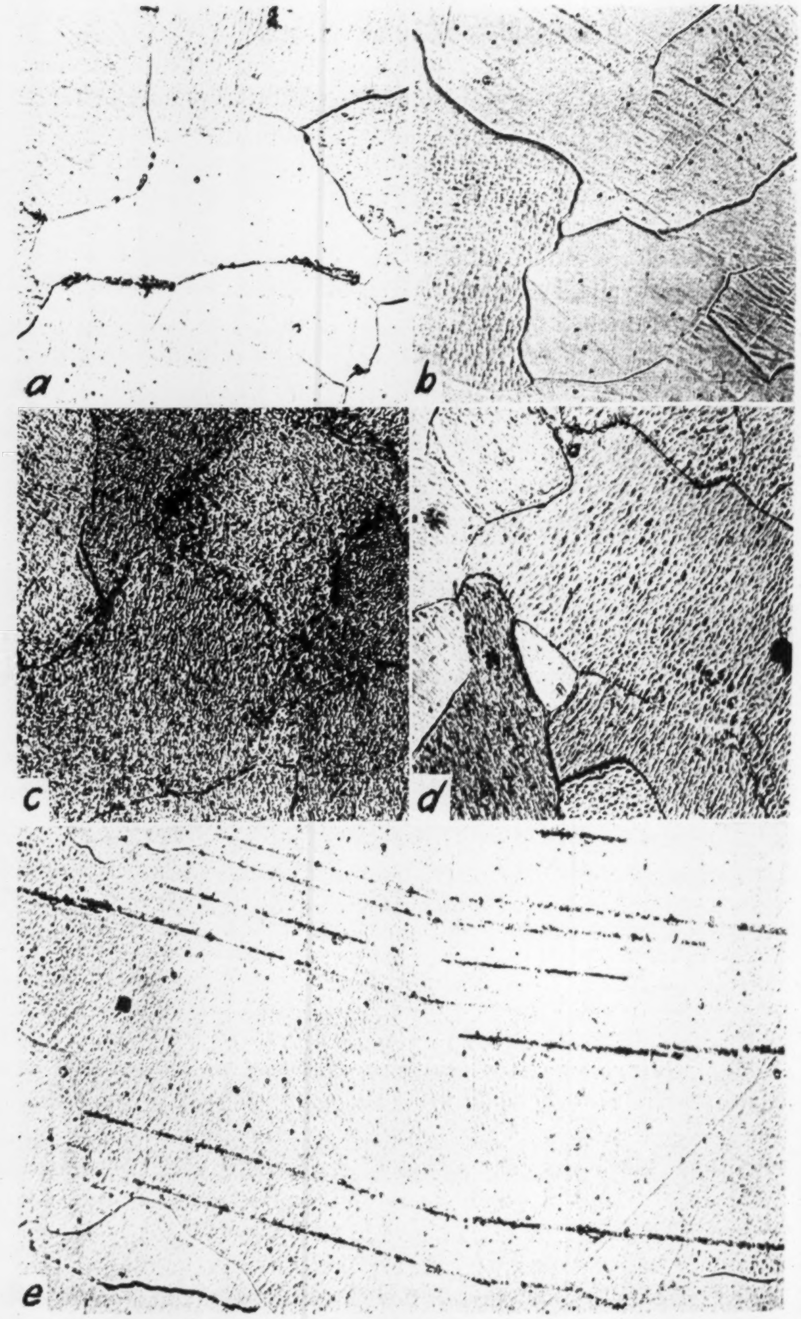

FIG. 28.—Precipitation Effects in Armco Iron (× 500).

(*a*) As received. Etched with 5 per cent picric acid in alcohol.

(*b*) Quenched from 650° C. (1200° F.). Etched with 5 per cent picric acid in alcohol.

(*c*) As received. Etched with Fry's micro-reagent.

(*d*) Quenched from 650° C. (1200° F.). Etched with Fry's micro-reagent.

(*e*) Quenched from 650° C. (1200° F.), slightly deformed and tempered 8 days at 200° C. (390° F.) Etched with 5 per cent picric acid in alcohol.

NOTE.—The solution of the grain boundary carbides on quenching from 650° C. (1200° F.); the darkening after etching with Fry's micro-reagent in the as received condition but not after quenching from 650° C. (1200° F.); and the precipitation in the slip lines after cold work and tempering. The nitrogen content of this sample of Armco iron was found to be 0.005 per cent.

Relation of Phosphorus to Nitrogen:

Although no comprehensive attempt was made to separate the effects of the elements concerned in embrittlement, still it was possible to do something in this direction. Thus rephosphorized open-hearth sheet bar high in phosphorus and low in nitrogen was obtained and also some nitrogenized low phosphorus iron, the nitrogen being introduced by adding potassium ferrocyanide.[1] Unfortunately, the carbon content of the two was not alike, the rephosphorized sheet bar containing 0.12 per cent carbon and the nitrogenized bar only 0.06 per cent carbon; the latter was also a thinner plate.

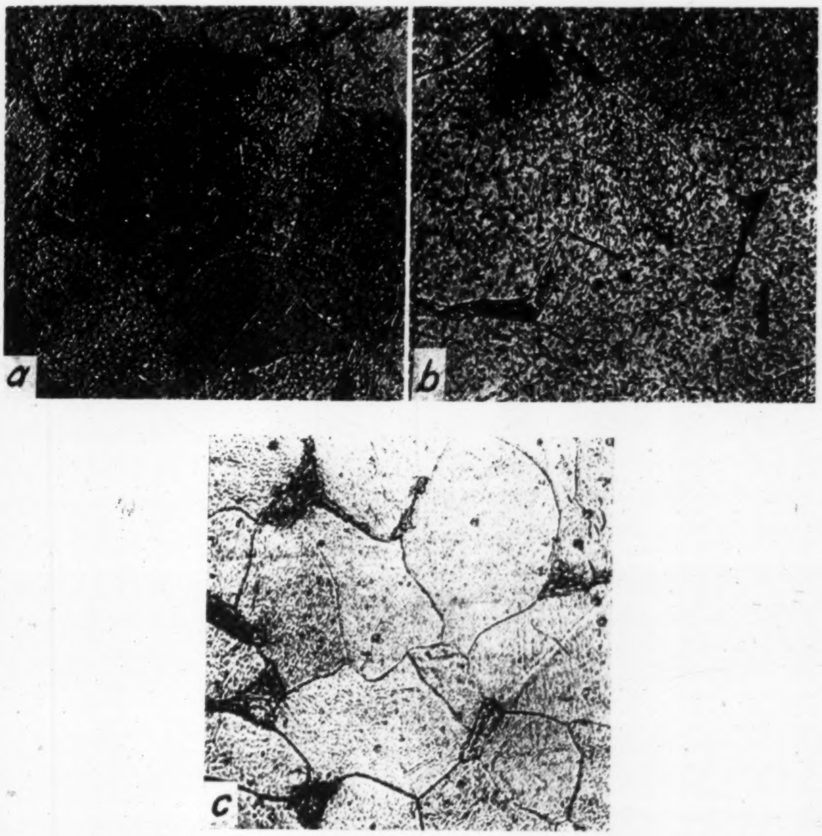

FIG. 29.—Precipitation Effects in Bessemer Steel. Etched with Fry's microreagent (× 500).

(a) As received—darkening as a result of precipitation.
(b) Heated 2 weeks at 100° C. (212° F.)—apparent coalescence.
(c) Quenched from 650° C. (1200° F.)—solution.

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[1] F. W. Scott, "Effect of Nitrogen on Steel," *Industrial and Engineering Chemistry*, Vol. 23, p. 1036 (1931).

However, the hole tension tests in Table XXXIV clearly indicate that phosphorus alone, even in as high amounts as are present in bessemer steel, does not cause embrittlement. The nitrogenized bar also gave high results, partly, no doubt, because of the low carbon content and the thin section used; microscopic examination indicated the nitrogen bearing constituent to be segregated in small patches and not uniformly distributed.

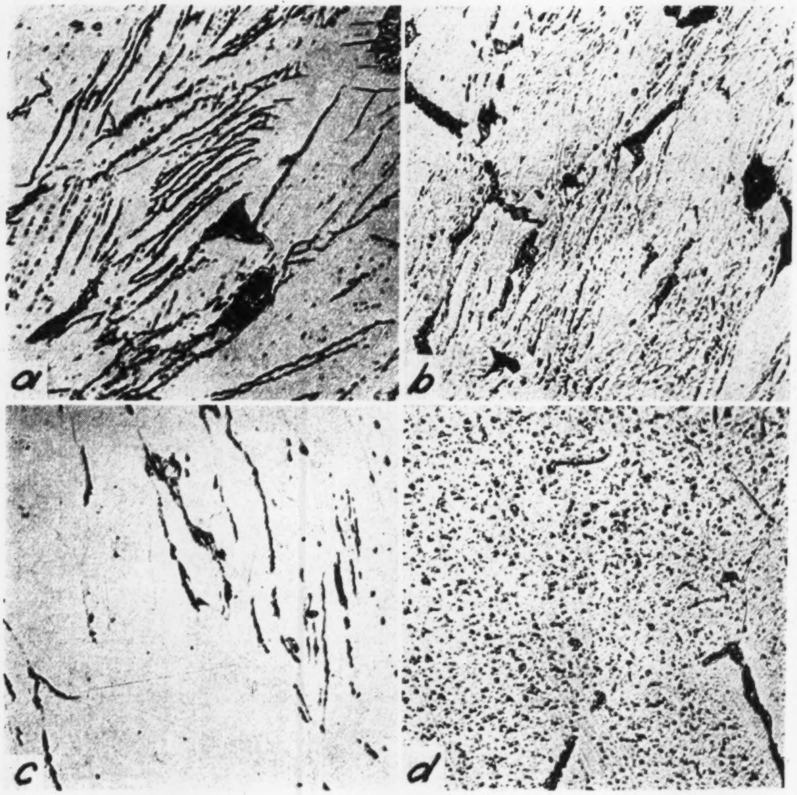

FIG. 30.—Precipitation Effects in Bessemer Steel (× 500).

(*a*) Compressed, then heated 2 weeks at 100° C. (212° F.). Note precipitation in slip lines. Etched with 5 per cent picric acid in alcohol.

(*b*) Cold worked ring about punched hole, heated 2 weeks at 100° C. (212° F.). Etched with 5 per cent picric acid in alcohol.

(*c*) Compressed, then heated 2 weeks at 100° C. (212° F.). Note precipitation in slip lines. Etched with boiling sodium picrate.

(*d*) Quenched from 650° C. (1200° F.) then heated 8 days at 200° C. (390° F.). Note precipitation throughout the grain. Etched with 5 per cent picric acid in alcohol.

Charpy impact tests after cold working of these materials gave similar results. Apparently the mutually acting effects of phosphorus and nitrogen (and no doubt carbon and oxygen) are necessary to cause embrittlement. It may be assumed perhaps, since the amount of phosphorus present is considerably below its accepted solubility limit, that this element does not itself precipitate but causes the nitrogen (or rather a compound of nitrogen with iron), for example, to precipitate along certain preferred planes in the crystal, causing more ready cleavage and consequent brittleness.

Precipitation Effects Revealed in Microscope:

As illustrated in the photomicrographs of Figs. 28 to 30, distinct precipitation effects after cold working, after quenching from 650° C. (1200° F), and reheating for long periods at 100 and 200° C. (212 and 390° F.) are shown in Armco iron and in bessemer steel. Such effects were revealed slightly in open-hearth steel, and not at all in Izett steel. In the cold-worked specimens precipitation occurred along slip lines after long-time tempering at 100 and 200° C. (212 and 390° F.). In this connection Fig. 30(*c*) is of interest, in that the darkening in the slip lines appeared after etching with sodium picrate. This reagent certainly has no tendency to "eat out" along grain boundaries or slip lines and thus affords better proof than can be obtained by using an acid reagent, which might give an erroneous impression of precipitation because of "eating out." The photomicrographs taken after etching with Fry's micro-reagent before and after quenching from 650° C. (1200° F.) indicate how ordinary iron and steel, which we usually consider free from precipitation phenomena, are really permeated with such effects. The marked rough-

TABLE XXXV.—RESULTS OF CHARPY IMPACT AND ROCKWELL HARDNESS TESTS OF COMPRESSED SPECIMENS BEFORE AND AFTER HEATING NINE DAYS AT 200° C (390° F.).

Specimens compressed 9 per cent.

Laboratory	Material	Energy Absorbed, ft-lb.		Rockwell Hardness Number, "B" Scale	
		Not Heated	Heated 9 Days at 200° C. (390° F.)	Not Heated	Heated 9 Days at 200° C. (390° F.)
No. 170....	6 × 6 × $\frac{1}{2}$ in. bessemer angle..........	2.2	1.6	91	85
No. 257....	6 × 6 × $\frac{1}{2}$ in. open-hearth angle.........	17.7	5.6	85	83.5
No. 343....	$\frac{13}{32}$-in. plate, Izett steel................	40.8	40.4	81	78.0
No. 525....	$\frac{1}{2}$-in. plate, ingot iron..................	28.7	26.6	74	73
No. 560....	$\frac{1}{2}$-in. plate, rephosphorized open-hearth sheet bar..........................	8.5	2.2	86	84
No. 587....	$\frac{3}{8}$-in. plate, nitrogenized open-hearth sheet bar 0.008 per cent nitrogen...........	38.7	17.5	81.5	80

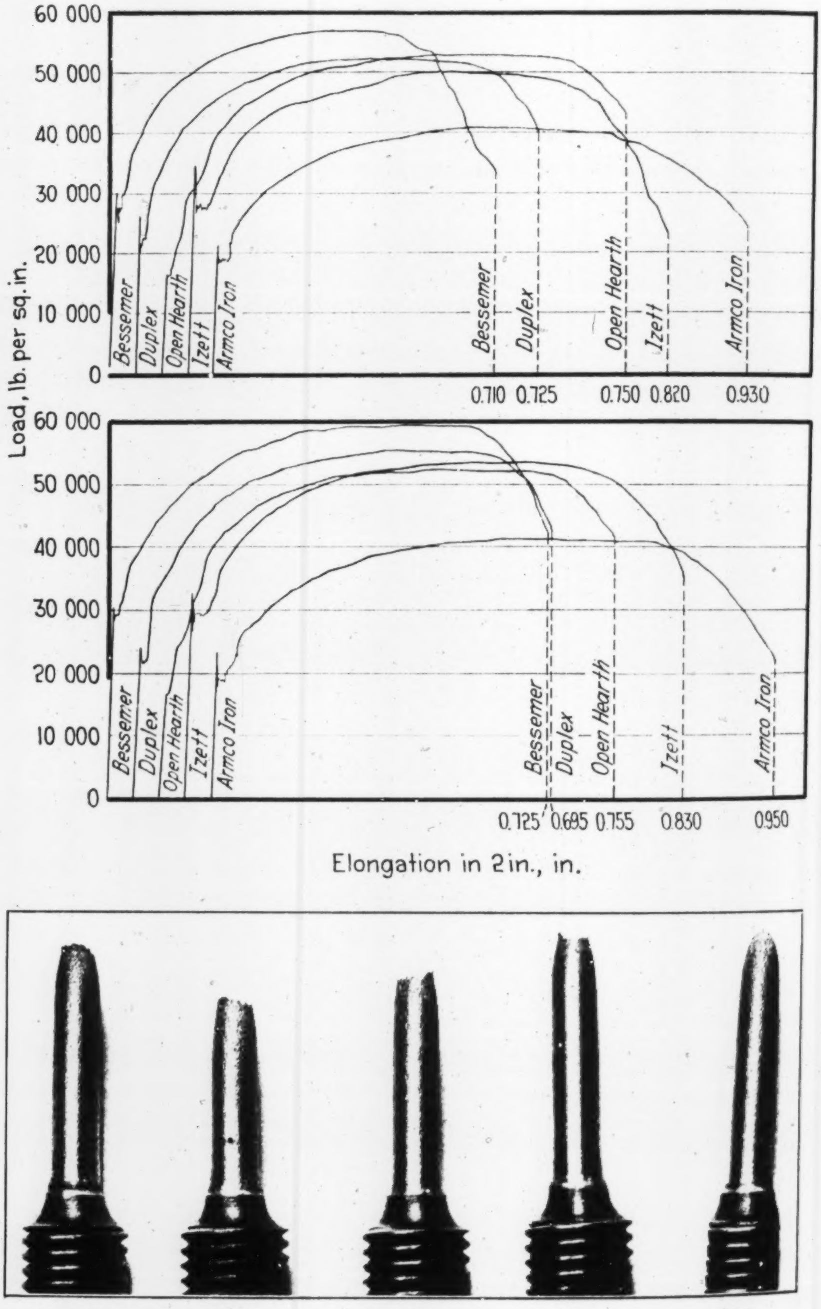

FIG. 31.—Duplicate Set of Stress-Strain Curves of Bessemer, Duplex, Open-Hearth, Izett, and Armco Iron Specimens Showing the Appearance of the Jog in the Curve at the Yield Point.

In the set of tested specimens below the curves, the very smooth surface of Izett as compared with the rest is indicative of its very fine grain.

ening and darkening of the surfaces before quenching from 650° C. (1200° F.) were in marked contrast to the smoother surfaces after quenching, except in Izett steel in which the appearance was about the same before and after quenching from 650° C. (1200° F.).

As may be seen in Table XXXV, heating the materials tested at 200° C. (390° F.) after cold working 9 per cent produced a decided lowering in impact resistance, except in Izett steel and Armco iron. It is noteworthy that this lowering in impact resistance was not accompanied by hardening. On the contrary there seemed to be a slight decrease in hardness, indicating that embrittlement need not necessarily be accompanied by hardening. As a matter of fact, the connection between either or both of the above effects and precipitation is still not very direct. The precipitation effects, which are shown in Figs. 28 to 30, were revealed upon tempering at 100 and 200° C. (212 and 390° F.); they did not appear upon tempering at 450° C. (840° F.) for either a short time, as in galvanizing, or for as long as five days, although we know galvanizing has an embrittling effect. Indeed it has been suggested on the basis of other evidence that solution of the impurities instead of precipitation may really be taking place.[1] Possibly the different impurities, nitrogen and oxygen for example, may precipitate out at different temperatures, let us say the nitrogen at the lower temperature and the oxygen at the higher. Again, the nitrogen compound, which may precipitate in larger amounts or can coalesce more readily, could be revealed in the microscope after tempering, whereas the oxygen compound[2] could not. On these assumptions heating at either the lower temperature (200° C., 390° F.), or the higher temperature (450° C., 840° F.) could cause embrittlement.

Stress-Strain Curves—Jog at Yield Point:

The stress-strain curves in Fig. 31, which were obtained by slowly loading the tension specimen at a constant rate of extension, are of interest in showing the pronounced drop in the beam which occurred at the yield point. It should be noted that in conformity with the hardness tests after cold working (Fig. 15) Izett steel also showed the least increase in strength with deformation. Contrary to a published report[3] both Armco iron and Izett steel showed well marked jogs in the stress-strain curve at the yield point. The fine texture of the tested Izett steel specimen, indicative of its fine grain, is also in striking contrast with those of the others.

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[1] Discussion by R. S. Dean of paper by L. R. Van Wert, "Some Notes on Blue Brittleness," *Transactions*, Am. Inst. Mining and Metallurgical Engs., Iron and Steel Division, Vol. 95, p. 238 (1931).

[2] It has been suggested that this may be MnO. G. d'Huart, "Embrittlement of Steel," *Science et Industrie*, Nos. 188 and 189, pp. 559, 636 (1929).

[3] C. W. MacGregor and F. R. Hensel, "The Influence of Nitrogen in Mild Steel on the Ability of Developing Flow Layers," *Journal of Rheology*, Vol. 3, p. 37 (1932).

In explaining hardening and embrittlement on the basis of the precipitation theory, the jog in the stress-strain curve at the yield point has not received sufficient consideration, but evidently the theory must account for this softening, as well as for the subsequent hardening. Typical solution and precipitation heat treatments and cold work markedly affect the shape of the stress-strain curve at the yield point.[1]

It is perhaps too fanciful to invoke Le Chatelier's principle here, but this may be helpful in picturing the mechanism. Pulling steel even below the elastic limit causes an increase in volume.[2] The steel must, therefore, so adjust itself as to neutralize this effect and can do so by taking any foreign matter present into solution (this is attended by a decrease in volume), thereby becoming stronger and attaining a yield point above the equilibrium value. Finally, however, the steel does yield, at which a disturbed state ensues, the metal becomes weak, and the drop in the beam occurs until recovery takes place by equilibrium being established or possibly by the precipitation of particles that can cause strengthening. The recent work of Van Wert[3] is of interest in this connection in showing "stepped yielding" in the blue heat temperature region. It would also be of interest to determine the course of the drop in the beam in the ordinary tension test at these temperatures, and also at zero and sub-zero temperatures. Altogether, a great deal remains to be done in clearing up the causes and mechanism of precipitation hardening and embrittlement.

RECOMMENDATIONS

With the results of this study so clear cut, there is little difficulty about recommendations. The "Achilles' heel" of the problem being the embrittlement of the large punched angles, the obvious immediate engineering remedy is to drill or sub-punch and ream these angles, as is recommended in the Tentative Recommended Practice for Safeguarding Against Embrittlement of Hot-Galvanized Structural Steel Products and Procedure for Detecting Embrittlement drawn up by Subcommittee X. Although this would in some cases entail a slightly increased cost, it should prove no great hardship. The large angles make up a rather small proportion of the total used in towers. Some fabricators do not have punching equipment for the heavier angles and would drill them in any event.

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[1] P. Ludwik and R. Scheu, "On the Yield Point in Electrolytic Iron and Low-Carbon Steel," Berichte der Fachausschüsse des Vereines Deutscher Eisenhüttenleute, Werkstoffausschuss, *Bericht No. 70* (1925).

[2] H. Hanemann and R. Yamada, "The Volume Changes in Steel Under Elastic and Plastic Stress," *Archiv für das Eisenhüttenwesen*, Vol. 4, p. 353 (1931).

[3] L. R. Van Wert, "Some Notes on Blue Brittleness," *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Iron and Steel Division, Vol. 95, p. 230 (1931). Discussion, p. 238.

Besides freedom from embrittlement, additional compensatory advantages for drilling or reaming are the increased breaking load borne by drilled or reamed angles, and the parallel walled holes obtained instead of the conical ones produced in the heavier punching operations. On the other hand, once the engineer is aware that punching the heavier sections involves the risk of embrittlement, he can probably in many instances make slight changes in design and use angles having longer legs but sections thin enough to be punched without risk, instead of smaller and thicker angles. The slenderness ratio $\frac{l}{r}$ on which are based the calculations for a safe compression load when the angle is used as a strut or column would be more favorable with the larger but thinner angle.

Assuming the use of structural steel conforming to the A.S.T.M. Specifications A 7 – 29,[1] or its equivelant, drilling the heavier angles ($\frac{3}{4}$ in. thick and over) should obviate the need for "embrittlement" testing in these sizes. There is no apparent need for testing steel meeting the A.S.T.M. Specifications A 7 – 29 in the small sizes, even when punched, nor does it seem probable that testing will be needed as a regular procedure in the medium size punched angles, although as to angles just under $\frac{3}{4}$ in. thick and as to duplex steel, additional data would be desirable before a fully positive and final conclusion can be drawn in this respect. It would appear, however, that for the great majority of medium size angles embrittlement testing will be superfluous except for investigational purposes or, for example, where construction at low temperatures is contemplated.

Electric resistance heating of the cold worked metal about the hole, as described in the report, might possibly prove practicable as a substitute for reaming. The use of a steel like Izett, which, when successfully made, can be safely punched in heavy sizes, cannot as yet be classed among the immediately available engineering recourses. Further development in the commercial manufacture of this type of steel may, however, offer another solution to the embrittlement problem. Further study of the underlying causes for the differences in different steels and different heats of steel in their propensity toward hardening and embrittlement by cold work, in their ability for or insensitiveness to precipitation hardening, and in their behavior at low temperatures would be valuable in pointing the way toward the precautions necessary in the production of steel insensitive to these influences.

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[1] 1930 Book of A.S.T.M. Standards, Part I, p. 67 (1930).

SUMMARY

The problem of embrittlement in galvanized structural steel angles for electrical transmission towers is discussed and methods of quantitative testing for such embrittlement about punched bolt holes are described. Data from a large number of tests on 170 heats of bessemer, duplex, and open-hearth steel in the as rolled, pickled, and galvanized conditions, with punched and drilled holes, are presented.

In commercial structural steel embrittlement is confined almost solely to the largest size punched angles. Punching is the principal factor in embrittlement. Pickling, galvanizing, the nature of the steel (in the case of commercial steel conforming to A.S.T.M. Specifications A 7 – 29), and the temperature of testing, play secondary, minor, or negligible rôles. Avoidance of punching in the heavy size angles is necessary and generally sufficient to avoid injurious embrittlement difficulties in present-day commercial galvanized structural steel angles.

DISCUSSION

MR. V. L. GLOVER[1] (*by letter*).—Mr. Epstein in his paper describing the work carried out at Battelle Memorial Institute in determining the cause of embrittlement in steel makes the statement that compared with embrittlement caused by punching, embrittlement caused by pickling and galvanizing may be classed as a minor factor.

A very pronounced case of embrittlement of steel wire, caused apparently by hydrogen occlusion during pickling, was encountered at a manufacturer's plant during the inspection of a large order of galvanized chain-link road-guard fabric. The fabric was manufactured from No. 4 gage (diameter 0.225 in.) cold-drawn steel wire and was galvanized after weaving. It was woven so that sharp bends (180 deg.) were made at the ends of the pickets where they are turned back over each other to form the knuckles. During final inspection it was discovered that many of the knuckles were brittle and snapped off at the bends upon the application of a very slight pressure.

The brittleness was attributed to the occlusion of hydrogen during the pickling process. This conclusion seemed logical for the reason that there was no evidence of brittleness in the woven fabric before it was pickled, but brittleness was very apparent when the fabric came out of the acid solution. The embrittlement was confined to the bends where the grain or structure of the metal was disturbed by cold bending. There was no evidence of brittleness except in the bends. We have observed a few other instances of steel wire embrittlement and in each case it has occurred where the metal was affected by bending. Apparently the bending opens up the grain of the metal sufficiently to permit the entrance of the hydrogen.

Observations were made to determine the effect of varying the length of time the fabric remained in the acid bath, and it was found that pronounced brittleness developed in a period as short as 30 seconds; material immersed for as long as 30 minutes showed no increase of brittleness after the first 4 or 5 minutes. The galvanizing process seemed to have no further effect. If the material was brittle when it entered the zinc, it was still brittle when it came out.

The wire that caused most of the trouble all came from the same mill and consisted of several large shipments representing many heat numbers. Another supply from a different mill caused only occasional trouble. Shipments from a third mill caused no trouble whatever, indicating that wire from one source is more susceptible to embrittlement by pickling than wire from another source. The wire from all three of the mills showed similar physical properties and complied in all respects with the Society's Standard Specifications for Cold-Drawn Steel Wire for Concrete Reinforcement (A 82 - 27). No chemical examination of the wire was made.

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[1] Engineer of Materials, Illinois State Division of Highways, Bureau of Materials, Springfield, Ill.

It was suggested that embrittlement caused by hydrogen occlusion would disappear after several days, but this did not prove true. The knuckles appeared to be just as brittle after several days as at the start. One shipment held in stock for two months showed no decrease in the degree of brittleness.

As a remedy for the trouble, a commercial inhibitor was added to the pickling solution but did not prove effective. The use of a pickling agent that would act on the surface of the metal without evolving hydrogen was suggested, and nitric acid was tried. A weak solution of nitric acid containing about ½ per cent of acid was used. This solution proved effective as a pickling agent and entirely eliminated the brittleness. It was the practice at this plant, however, to run the material direct from the pickling bath to the zinc bath without washing, and it was found that the nitric acid adhering to the material increased the dross on the surface of the molten zinc. It is reasonable to assume that excessive dross would have been avoided if the material had been washed to remove the acid before allowing it to pass into the zinc.

From this we believe that the embrittlement of steel caused by the occlusion of hydrogen during pickling in hydrochloric or sulfuric acid can be eliminated by the use of a pickling agent that does not evolve hydrogen by contact with iron, and that the use of a dilute solution of nitric acid as a pickling agent has possibilities.

MR. H. H. MORGAN[1] (*by letter*).—The Battelle Memorial Institute is to be complimented on its most comprehensive and thorough attack of this investigation and the conclusive results obtained.

Judgment of embrittlement is based on ductility shown by bending tests of angles with holes punched or drilled in the vertical leg of the angle. With punched holes, approximately 45 per cent of the angles ¾ in. in web thickness and heavier show "embrittlement." And yet Mr. Epstein stated early in his paper that there was only one recorded failure. Certainly there have been at the most only a very few failures in service. Does not this mean that the distinction between satisfactory ductility and injurious embrittlement is perhaps not fairly defined to correlate with service conditions? Perhaps a "merit number" somewhat below 10 should be the line of distinction.

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[1] Manager, Rail and Fastenings Dept., Robert W. Hunt Co., Chicago, Ill.; also Chairman of the Society's Committee A-1 on Steel.

The report proves that the main item of so-called embrittlement is the cold punching of holes in the heavier materials and that matters of process of steel manufacture, pickling, and galvanizing are only of secondary or negligible significance.

"Embrittlement as an engineering problem would practically cease to exist" if the holes in members $\frac{3}{4}$ in. or thicker were either drilled or sub-punched and reamed. This is a matter of workmanship and not material. And, as a matter of fact, such a practice is standard on fabricated structural steel where the best class of workmanship is desired. Is not the answer then to specify such workmanship details in specifications for transmission tower construction? Such requirements are thoroughly practical and would add only incidental cost items.

I believe that transmission towers warrant the best class of workmanship and, in this connection, it is of interest to consider design, workmanship, and materials for such construction, any one of which, if not properly considered, would result in failures.

Design.—There seems to have been no question raised as to the design where failures have occurred and perhaps they were not questionable designs. However, the stresses on transmission towers are very complex and economy dictates that they be designed with as high unit stresses as will be safe. Also, the stresses are likely to be much higher during the period of erection and line stringing than after the transmission line is in operation. These design items are fully recognized by anyone familiar with such matters and it is quite the general practice to make destruction tests of fully erected towers in order to check the design.

Workmanship.—Workmanship implies care and precision in fabrication, including proper holing and proper bolt or rivet fits. Most transmission tower work is assembled in the field and the best character of bolt fits and other such matters are not always obtained. Expecting a proper shear bearing in a bolt through punched holes in $\frac{3}{4}$ in. thick material is asking a little too much and high stresses must develop in such a connection. In other words, in bolted connections, unless they are through drilled or reamed holes, very high stresses may result even in most conservative design.

Materials.—Engineers have generally been of the opinion that the Society's Standard Specifications for Structural Steel for Bridges

(A 7 – 29) will give suitable material for galvanizing and use in transmission tower construction. This research work has now proved this in a clear-cut, definite manner; use material conforming to Specifications A 7 and drill or sub-punch and ream the holes in $\frac{3}{4}$ in. and heavier material. The Battelle Memorial Institute has certainly done a fine piece of work in arriving at such definite results.

In conclusion, I might mention two instances where materials have been charged with brittleness when conditions of design or of workmanship were the essential causes. (1) Quite an amount of old structural steel used in bridges has failed through cracks emanating from punched bolt holes. In a number of cases it has been proved that these are simply fatigue failures due to over-stressing structures that were designed for the lighter loadings of 20 years ago. (2) A hole can be burned through the web of a steel rail with an acetylene torch and the rail will snap in two without ductility if dropped, yet that same rail with a drilled hole will not be embrittled. No one charges the failure of that rail to the material of the rail.

MR. SAMUEL EPSTEIN[1] (*author's closure by letter*).—The statement in the paper referred to by Mr. Glover "that compared with embrittlement caused by punching embrittlement caused by pickling and galvanizing may be classed as a minor factor" was intended to apply to the very specific problem studied, that of embrittlement about the hole in structural steel angles. It was amply supported by the data given; only after severe punching did embrittlement occur; there was no embrittlement with drilled holes.

For other materials and for other forms of embrittlement, as in sheet or wire, the case may be different. On this the writer has no first-hand evidence. It seems significant, however, that the failures of the wires mentioned by Mr. Glover also occurred at the bends, that is, where they were locally cold worked.

It is difficult to differentiate between embrittlement in pickling from that in galvanizing when the latter is superimposed on the former. To separate the effects, samples should be galvanized without pickling, as described in the paper. For punched structural steel angles, the same degree of embrittlement was obtained upon galvanizing without pickling as when galvanizing after pickling, the conclusion being reached that during the heating in galvanizing the effects of hydrogen embrittlement were removed to be replaced by the embrittling effect of galvanizing. In wire and sheet, galvanizing may not entirely remove the effects of hydrogen embrittlement. Van de Loo[2] has recently reported that in drawn steel wire galvanizing removed the effects of pickling in hydrochloric acid, but not entirely of pickling in sulfuric acid.

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[1] Metallurgist, Battelle Memorial Inst., Columbus, Ohio.

[2] H. Van de Loo, W. Püngel, and E. H. Schulz, "The Influence of Pickling and Zinc Coating on the Tensile Properties of Drawn Steel Wire," *Stahl und Eisen*, Vol. 51, p. 1585, 1931.

It is not clear whether the brittle pickled wire referred to, which did not recover its ductility on standing, was also galvanized. If it were, it would indicate that cold work followed by galvanizing was the cause of the embrittlement rather than pickling, for as a rule pickling embrittlement tends to disappear on standing, whereas galvanizing embrittlement does not.

The writer is indebted to Mr. Morgan for so clearly classifying the parts played by design, workmanship, and material in the construction of transmission towers. In regard to the merit number of 10 which was used for drawing the line between ductility and brittleness, an endeavor was made to set a figure which would ensure adequate safety. Whether it is too high, as Mr. Morgan would imply, or too low, is for engineers to determine, as further experience is obtained with the angle bend test in the building of transmission towers.

A CORRELATION OF SOME MECHANICAL AND MAGNETIC PROPERTIES OF 1.21-PER-CENT CARBON TOOL STEEL[1]

By J. V. Emmons[2] and R. L. Sanford[3]

Synopsis

This paper presents the results of an investigation of the relationships between certain mechanical and magnetic characteristics of a high-carbon tool steel. Six materially different physical properties were measured, three of which were mechanical and three magnetic. An outstanding conclusion drawn from the results is that each property has its own individuality which is distinct from that of the other properties. Relationships between the several properties are not always obvious and when they do appear to exist it may be for only a limited range of heat treatments. This behavior indicates that the changes taking place during the heat treatments examined are very complex in their nature. It should not be concluded that magnetic analysis is of no value, but only that it should be applied with a full knowledge of the limitations of the method and within the range in which correspondence is known to exist.

Introduction

In connection with the work of the Society's Committee A-8 on Magnetic Analysis, it has many times been observed that lack of fundamental knowledge of the relationships between the magnetic and mechanical properties of steel constitutes a serious handicap in the development of practical testing methods. In previous experiments with hardened steels, such as the twist drill tests carried out by the committee,[4,5] the variables have been so numerous and so difficult to control that general conclusions have been difficult to draw. Two factors in particular have contributed to this difficulty, namely, the choice of materials of complex composition, such as high-speed steel, and the difficulty of making satisfactory mechanical tests on hardened steel.

In planning the present investigation, an effort was made to minimize these two difficulties so far as possible, first, by choosing a simple carbon tool steel as a material, and, second, by adopting a method of mechanical test developed by one of the authors which has proved to be especially suited to the testing of hardened material. In this way, it was hoped that some clue might be obtained as to the fundamental relationships between the magnetic and mechanical properties of hardened tool steel.

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[1] Publication approved by the Director of the Bureau of Standards of the U. S. Department of Commerce.

[2] Metallurgist, The Cleveland Twist Drill Co., Cleveland, Ohio.

[3] Chief, Magnetic Section, U. S. Bureau of Standards, Washington, D. C.

[4] Report of Committee A-8 on Magnetic Analysis, *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part I, p. 170 (1923).

[5] W. B. Kouwenhoven, "Magnetic Test of A.S.T.M. Drills," *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part II, p. 635 (1924).

APPARATUS AND MATERIAL

Mechanical Tests:

The mechanical tests were made with the torsion testing apparatus previously used and described by one of the authors.[1] With this apparatus, observations of torque and angular deformations are made from which values of ultimate torque and factors representing plasticity and toughness can be deduced. The form and dimensions of the specimen used for the torsion test are shown in Fig. 1 of the previous paper.[1] Hardness determinations were made by the Rockwell method.

Magnetic Tests:

On account of the small size and irregular shape of the specimen, it was not feasible to make the magnetic tests with a permeameter of the usual type. A special magnetic comparator similar in principle to the apparatus previously described by Fischer[2] was therefore constructed. In this apparatus, two specimens, one of which has been calibrated in a permeameter, are clamped in parallel across the poles of a suitable electromagnet. By means of test coils surrounding the specimens and a ballistic galvanometer, the inductions in the two specimens resulting from the same value of magnetizing force are compared. By reference to the curve for the known specimen, data can be obtained for the curve of the specimen under test. As this is a somewhat tedious procedure, the test was simplified by omitting the standard specimen and substituting the reading of magnetizing current for the determination of the magnetizing force by the indirect method indicated above. Since only comparative values were required for our purpose, this procedure was justified by the fact that for this type of magnetic circuit the magnetizing force is proportional to the current.

Thermomagnetic Analysis:

In addition to the magnetic tests made on the torsion specimens, thermomagnetic tests were run on a supplementary set of specimens made from the same material but cylindrical in form. The apparatus used was similar to that previously described by one of the authors.[1] The specimen is heated in a water-jacketed electric furnace surrounded by a magnetizing solenoid. The changes in magnetization brought about by heating or cooling are observed by means of an astatic magnetometer.

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[1] J. V. Emmons, "Some Physical Properties of Hardened Tool Steel," *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part II, p. 47 (1931).

[2] M. F. Fischer, "Apparatus for the Determination of the Magnetic Properties of Short Bars," U. S. Bureau of Standards *Scientific Paper No. 458*, Vol. 18, p. 513 (1922).

Material:

The material chosen was a simple carbon tool steel of the following chemical composition:

Carbon, per cent	1.21
Manganese, per cent	0.17
Phosphorus, per cent	0.011
Silicon, per cent	0.14
Sulfur, per cent	0.008
Chromium, per cent	none

The raw material was in the form of a coil of wire rod. This coil was carefully inspected at both ends for uniformity while in the annealed condition. In order to secure a reliable average of the results and show something of the magnitude of the experimental error, three specimens were prepared for each variation in heat treatment.

Heat Treatment.—In order to make available for examination a large number of controlled variations in physical properties, a schedule of heat treatments was prepared introducing five variations in hardening temperature and seven variations in tempering temperature. This schedule was intended to cover the range of heat treatments commonly regarded as useful for this steel, with some overlapping beyond the regions of usefulness.

Every effort was made to eliminate all variables which were not controlled and under observation, and microscopic examination was made of the structures developed by all heat treatments to aid in the proper interpretation of the results.

The schedule of heat treatments was as follows:

	TEMPERING TEMPERATURES						
HARDENING TEMPERATURES	NONE	200° F. (95° C.)	300° F. (150° C.)	400° F. (205° C.)	500° F. (260° C.)	600° F. (315° C.)	700° F. (370° C.)
1400° F. (760° C.)	x	x	x	x	x	x	x
1450° F. (785° C.)	x	x	x	x	x	x	x
1500° F. (815° C.)	x	x	x	x	x	x	x
1550° F. (840° C.)	x	x	x	x	x	x	x
1600° F. (870° C.)	x	x	x	x	x	x	x

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[1] R. L. Sanford, "Apparatus for Thermomagnetic Analysis," U. S. Bureau of Standards *Journal of Research*, Vol. 2, p. 659 (1929).

OBSERVATIONS AND RESULTS

Preliminary Magnetic Tests:

After the specimens had been quenched, but before the tempering operation, they were all given a magnetic test. The purpose of this preliminary test was to make sure that the specimens had responded uniformly to the hardening treatment.

The first set of specimens showed a rather wide variation in magnetic induction corresponding to a magnetizing current of 3 amperes. The amount of this variation ranged from 19.3 per cent for the 1500° F. (815° C.) quench to 1.6 per cent for the 1550° F. (840° C.) quench. Although the schedule for tempering was arranged to give as nearly average results as possible, the observed variations in mechanical properties ranged from 17 per cent to 35 per cent for a given heat treatment. The cause of this variation was found to lie in the use of an insufficiently drastic quench in hardening the specimens. For this reason a new set of specimens was prepared with much better success.

TABLE I.—MAGNETIC PROPERTIES.

Induction in kilogausses. Current in amperes, $I_{max} = 3.00$ amperes.

Hardening Temperature		Tempering Temperature						
		None	200° F. (90° C.)	300° F. (150° C.)	400° F. (205° C.)	500° F. (260° C.)	600° F. (315° C.)	700° F. (370° C.)
1400° F. (760° C.)	B_m	15.98	15.88	16.05	17.12	19.12	19.09	19.10
	B_r	9.54	9.48	9.49	10.50	12.76	13.33	13.74
	I_c	0.49	0.48	0.40	0.32	0.20	0.20	0.18
1450° F. (785° C.)	B_m	15.52	15.47	15.47	16.62	19.27	19.05	19.12
	B_r	9.10	9.07	8.91	9.98	12.69	13.09	13.66
	I_c	0.45	0.46	0.40	0.34	0.20	0.20	0.20
1500° F. (815° C.)	B_m	14.90	14.81	15.00	16.20	19.30	19.20	19.20
	B_r	8.44	8.41	8.40	9.40	12.34	12.96	13.44
	I_c	0.44	0.44	0.40	0.32	0.21	0.20	0.20
1550° F. (840° C.)	B_m	14.18	14.09	14.10	15.52	19.45	19.29	19.33
	B_r	7.58	7.49	7.34	8.46	11.65	12.33	12.93
	I_c	0.43	0.42	0.40	0.34	0.22	0.21	0.21
1600° F. (870° C.)	B_m	12.78	12.73	12.90	15.08	19.61	19.51	19.60
	B_r	6.06	6.07	6.10	7.72	11.15	12.15	12.36
	I_c	0.42	0.41	0.37	0.34	0.23	0.22	0.23

For the second set of specimens quenched more drastically, the uniformity of response to the quenching operation as indicated by the magnetic test was very satisfactory. In no case did the induction corresponding to a magnetizing current of 3 amperes vary by more than one per cent, which is about the limit of the experimental error.

Final Magnetic Tests:

After tempering, the Rockwell hardness was determined before making the magnetic tests. Several weeks elapsed before the magnetic tests could be carried out, and hardness determinations repeated after the magnetic tests were completed indicated that some aging had taken place in the untempered specimens. It is not known whether there was a corresponding change in the magnetic properties. The specimens which had been hardened at 1600° F. (870° C.) developed cracks, apparently resulting from the indentations produced by the hardness test, and another set was substituted. The hardness was not determined for these specimens until after the other tests had been made.

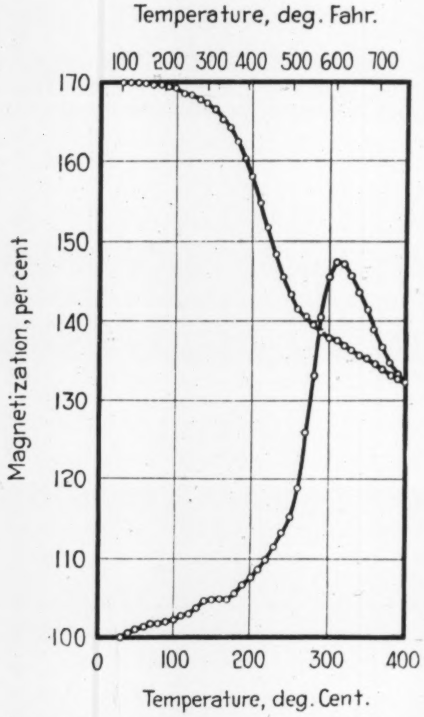


FIG. 1.—Magnetization-Temperature Curve for Specimen Quenched from 1600° F. (870° C.).

The data obtained by the magnetic tests included values of maximum induction, B_m, residual induction, B_r, and the the current corresponding to the coercive force, I_c, all taken from a maximum magnetizing current of 3 amperes. The variations among specimens which had received the same treatment were very small, not exceeding one per cent. The average results are given in Table I.

Mechanical Tests:

The observations made in the torsion tests included ultimate torque, ultimate deformation and plastic deformation. Rockwell hardness determinations were also made. These results have been presented in Figs. 3 to 9, inclusive, and are discussed later.

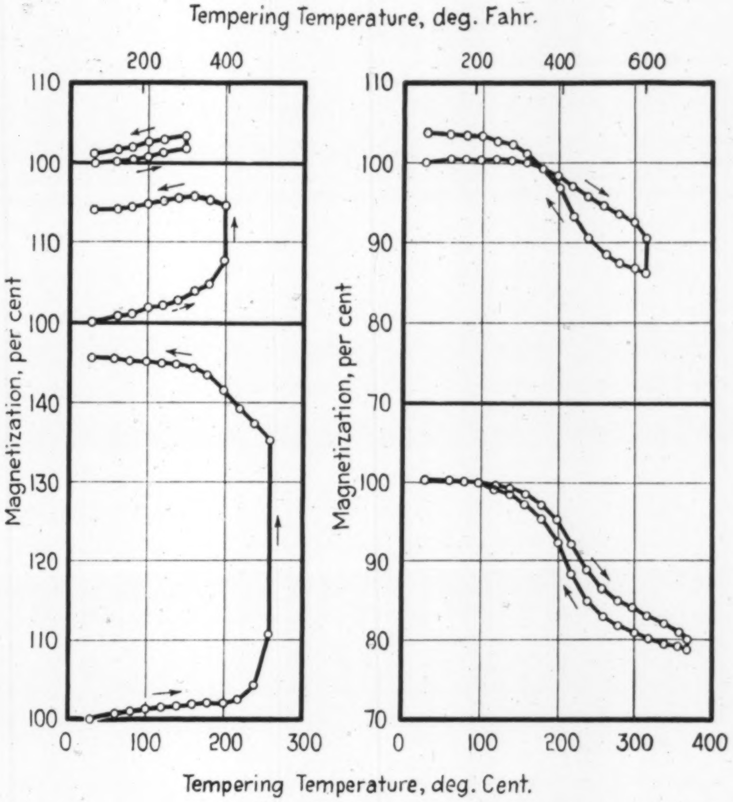


FIG. 2.—Thermomagnetic Analysis Curves Showing Changes Due to Holding at Various Tempering Temperatures.

Thermomagnetic Analysis:

The curve of Fig. 1 is typical of the results of thermomagnetic analysis runs made for each of the quenching temperatures employed. Heating was carried to 400° C. (750° F.) in each case. The curves all had similar characteristics, the principal differences being in the temperature at which the maximum occurred on heating, the magnitude of the peak, and the temperature at which the A_0 transformation appeared to be complete.

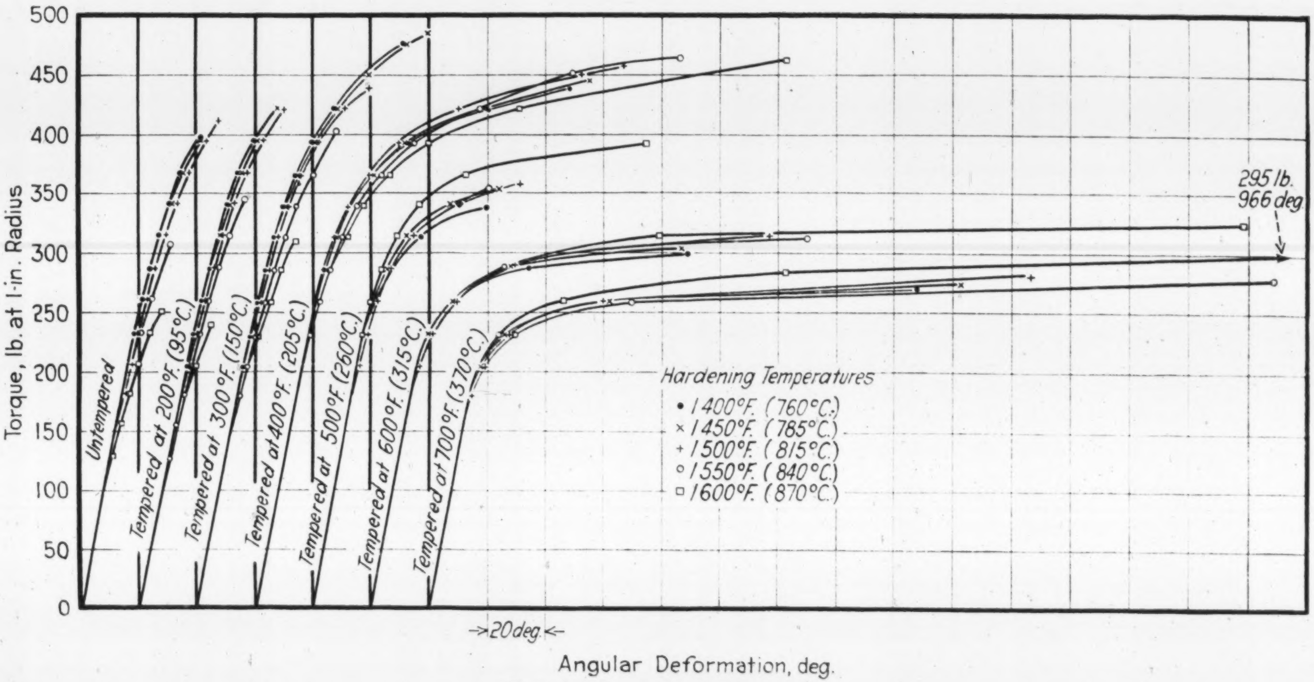


FIG. 3.—Stress-Strain Curves.

Another experiment consisted in heating a specimen quenched at 1600° F. (870° C.) successively to each of the tempering tempera-

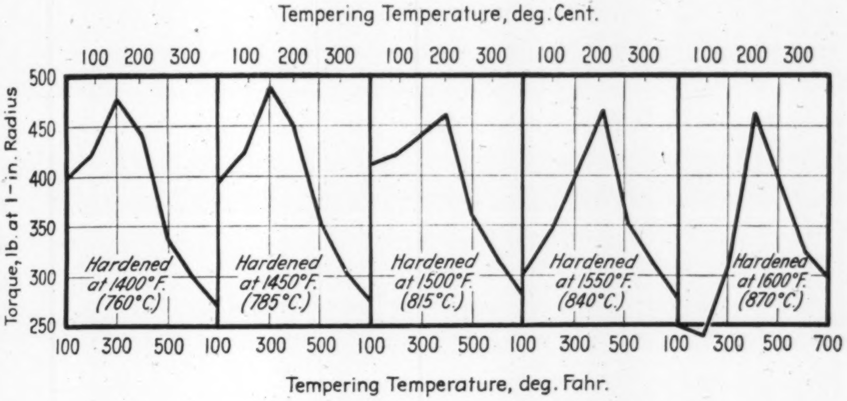


FIG. 4.—Relation of Torque to Tempering Temperatures.

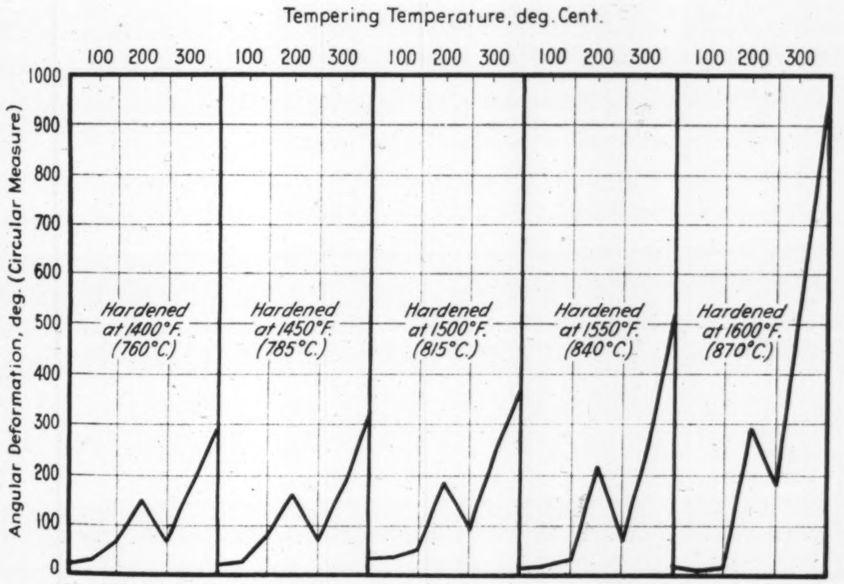


FIG. 5.—Relation of Plastic Deformation to Tempering Temperatures.

tures used, holding the temperature constant for thirty minutes, and cooling, noting the resulting changes in magnetization. This treatment corresponded as nearly as possible to that given the torsion specimens in the tempering operation. The results are shown graphically in Fig. 2. Values of magnetization are plotted in terms of the per cent of the value at room temperature.

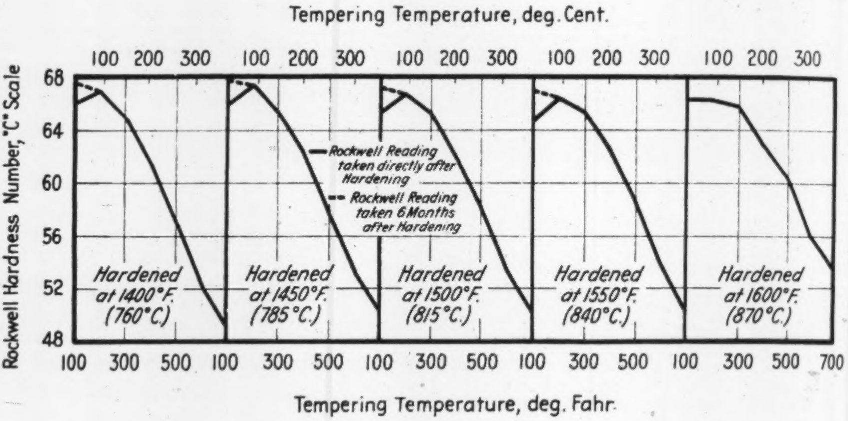


FIG. 6.—Relation of Rockwell Hardness to Tempering Temperatures.

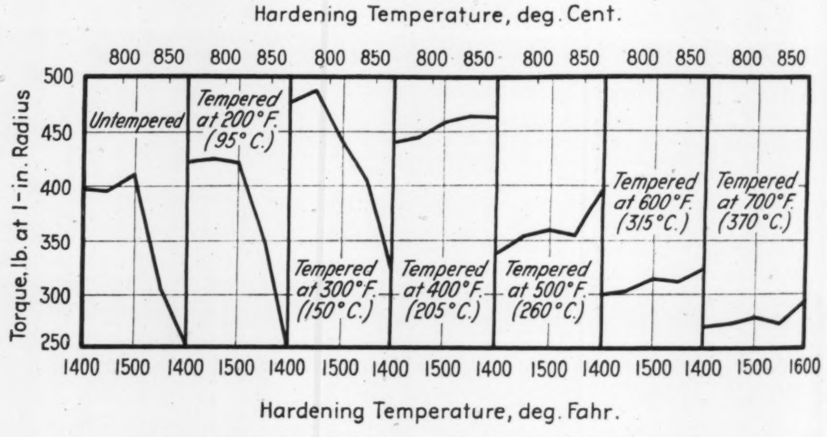


FIG. 7.—Relation of Torque to Hardening Temperatures.

DISCUSSION OF THE DATA

Analysis of the Mechanical Properties:

A general picture of the results for strength and plasticity is given by the stress-strain curves in Fig. 3. The behavior here shown is examined in detail in the following analysis.

Curves have been plotted showing the relation of the ultimate torque to the tempering temperature for each of the five hardening temperatures as shown in Fig. 4. Study of these curves shows that in all cases the strength rises to a maximum with increasing tempering temperatures. This maximum of strength at the lower hardening temperatures occurs upon tempering at 300° F. (150° C.), but at hardening temperatures of 1500° F. (815° C.) and higher it occurs at 400° F. (205° C.). The downward slope of the curve after passing the maximum, is similar for all hardening temperatures.

The plastic deformation as shown in Fig. 5 also rises with increasing tempering temperature to a maximum at 400° F. (205° C.).

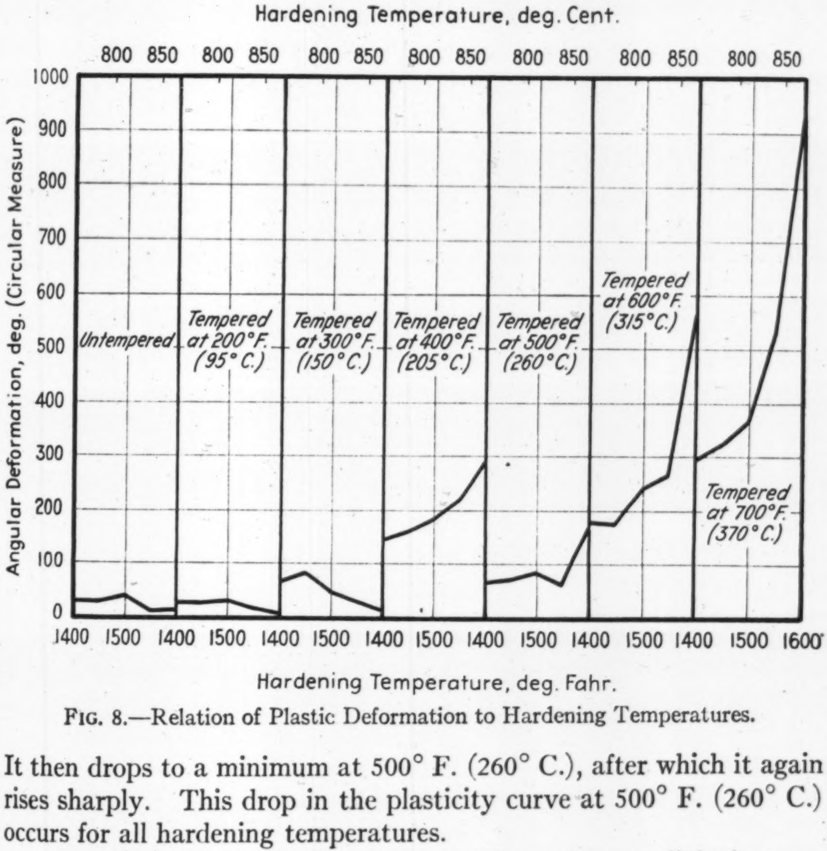


FIG. 8.—Relation of Plastic Deformation to Hardening Temperatures.

It then drops to a minimum at 500° F. (260° C.), after which it again rises sharply. This drop in the plasticity curve at 500° F. (260° C.) occurs for all hardening temperatures.

The Rockwell hardness as shown in Fig. 6 shows a slight increase to a maximum at 200° F. (95° C.). A similar increase in hardness is produced by aging at room temperature for about six months. After passing the maximum at 200° F. (95° C.), the hardness decreases moderately at 300° F. (150° C.) and more rapidly with higher tempering temperatures.

When the ultimate torque is plotted against hardening temperatures as in Fig. 7, it is seen that the effect of the hardening temperatures upon the strength is much more pronounced for the lower tempering temperatures than it is for those of 400° F. (205° C.) and higher. At the lower tempering temperatures the strength decreases greatly with an increase in hardening temperature while at the higher tempering temperatures the strength slightly increases.

When the plastic deformation is plotted against the hardening temperatures (Fig. 8) it is seen that the effect of the hardening temperatures upon the plasticity is small up to a tempering temperature of 300° F. (150° C.). With higher tempering temperatures, the effect of the variation in hardening temperatures becomes increasingly more pronounced until at 700° F. (370° C.) increasing hardening temperatures produce an enormous rise in the plasticity.

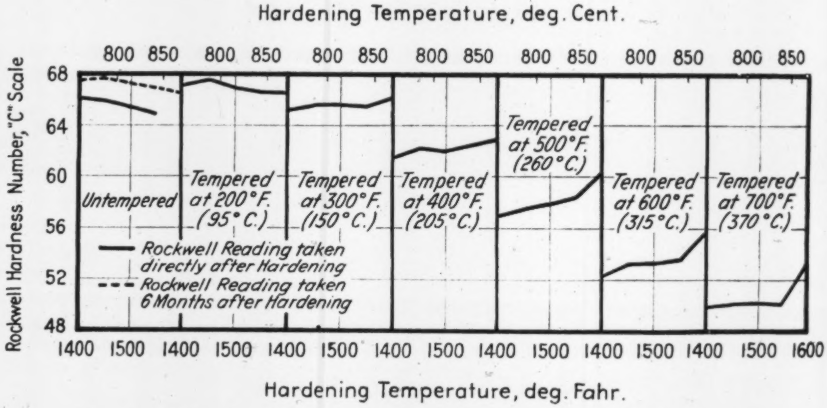


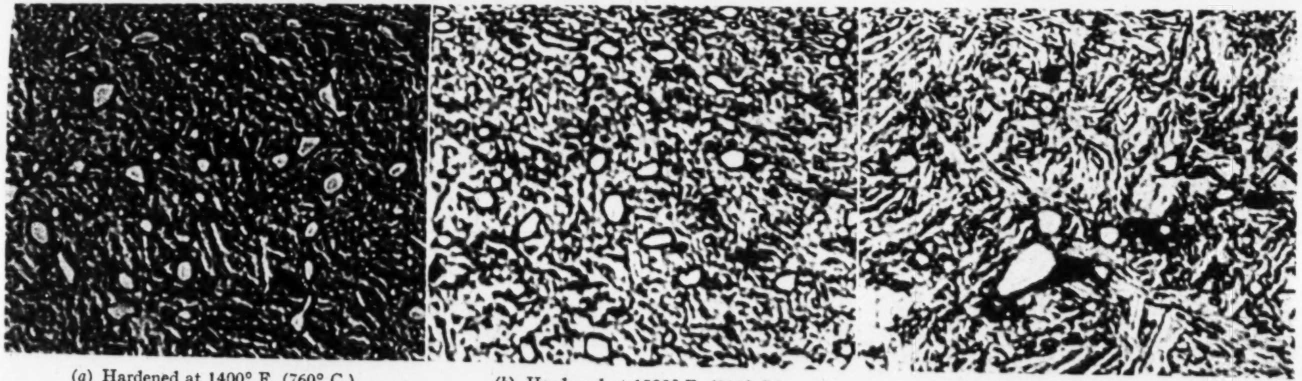
FIG. 9.—Relation of Rockwell Hardness to Hardening Temperatures.

When the Rockwell hardness is similarly plotted against variable hardening temperatures as shown in Fig. 9, the effect of changes in the hardening temperatures is seen to be relatively small. It is observed that with no tempering the lowest hardening temperatures produce the highest hardness and the highest hardening temperatures the lowest hardness. With a 500° F. (260° C.) tempering temperature this curve is reversed with the lowest hardness when hardened at 1400° F. (760° C.), and the highest when hardened at 1600° F. (870° C.).

Correlation of the Mechanical Properties:

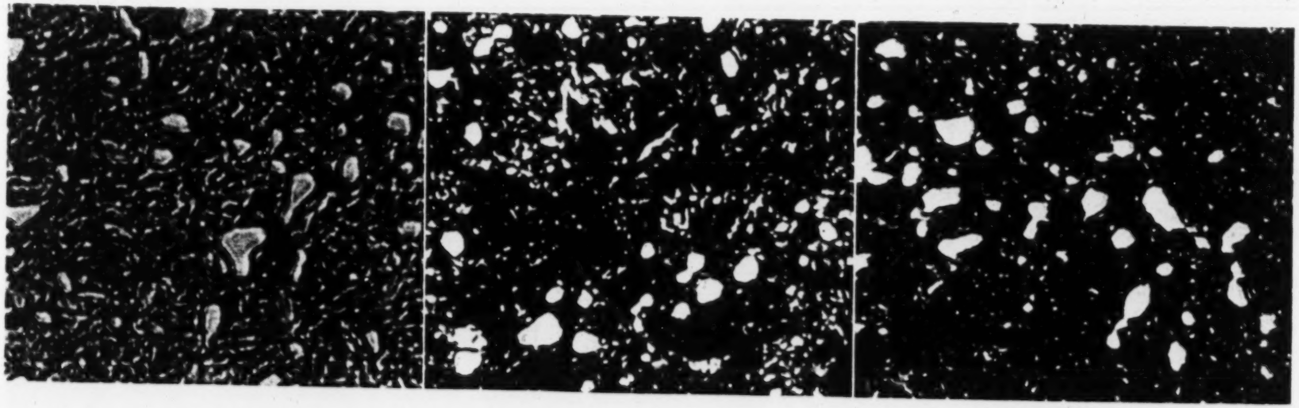
The most casual comparison of the curves for strength, plasticity, and hardness shows that each property has its own peculiar behavior and that general conclusions are difficult to draw.

A study of Figs. 4 to 6 shows that the effect of tempering at temperatures above 500° F. (260° C.) is to decrease the strength and



(*a*) Hardened at 1400° F. (760° C.). (*b*) Hardened at 1500° F. (815° C.). (*c*) Hardened at 1600° F. (870° C.).

FIG. 10.—Photomicrographs Showing the Effect of Several Hardening Temperatures upon the Structure Before Drawing (× 2000).



(*a*) Tempered at 300° F. (150° C.). (*b*) Tempered at 500° F. (260° C.). (*c*) Tempered at 700° F. (370° C.).

FIG. 11.—Structure as Hardened at 1500° F. (815° C.).

hardness while increasing the plasticity. Tempering at temperatures below 500° F. (260° C.) has a more complicated effect. It seems conclusive that the effect of tempering up to 300 to 400° F. (150 to 205° C.) is to increase both the strength and the plasticity. At a temperature of 500° F. (260° C.) strength, plasticity, and hardness all decrease.

A study of Figs. 7 to 9 shows two interesting peculiarities. At tempering temperatures of 300° F. (150° C.) and below, hardening at temperatures of 1550° F. (840° C.) and 1600° F. (870° C.) produces a sharp falling off of the strength but has only slight effect on the plasticity and hardness. At tempering temperatures of 400° F. (205° C.) and higher, increasing hardening temperatures are accompanied by a general increase in strength, plasticity, and hardness. This increase is particularly noticeable at the 1600° F. (870° C.) hardening temperature.

Microstructure:

Figures 10 (*a*), (*b*) and (*c*) are micrographs showing the effect of the several hardening temperatures upon the structure before drawing. The structure consists of a matrix of martensite with numerous masses of iron carbide or cementite. The martensite has the distorted or vermiform shape usually produced by heat treatment in this range.

Increasing the hardening temperatures has the general effect of increasing the size of the martensite masses and decreasing the number of carbides.

Figures 11 (*a*), (*b*), and (*c*) are micrographs showing the effect of increasing tempering temperatures upon the structure of specimens hardened at 1500° F. (815° C.). The changes produced by tempering are solely in the matrix. In Fig. 10 (*a*) which shows the structure of the material when hardened at 1500° F. (815° C.) but not tempered, the martensite occupies nearly the whole of the intercarbide area. With increasing tempering temperature, the martensite "worms" appear to break down at the outside edges first, causing a gradual shrinkage in size. This shrinkage of the martensite is accompanied by a concentration of the submicroscopic carbide in the remaining martensite area. This concentration appears to maintain the stability of the martensite. As the tempering temperature is raised, the carbide available in the martensite is able to stabilize smaller and smaller areas of martensite. The point where the martensite completely disappears and only carbide and ferrite remains, is outside the scope of this experiment. At the highest tempering temperature employed, 700° F. (370° C.), the martensite "worms" are mere remnants from

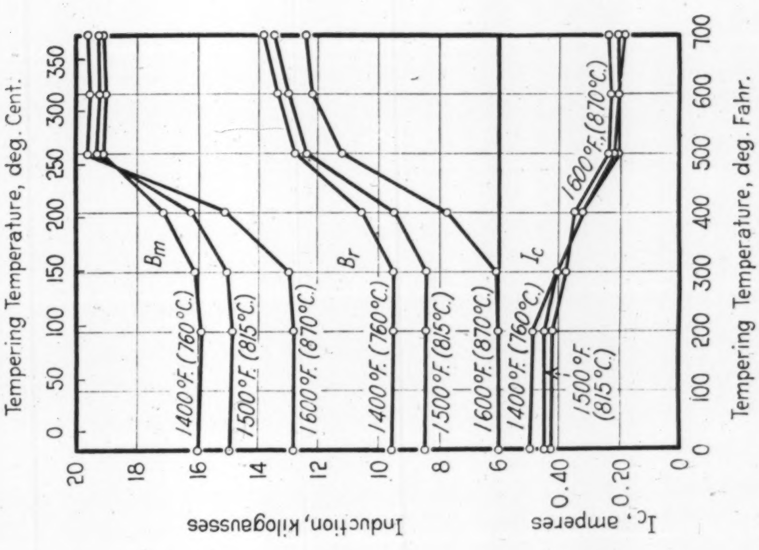


FIG. 13.—Effect of Tempering Temperature on Magnetic Characteristics.

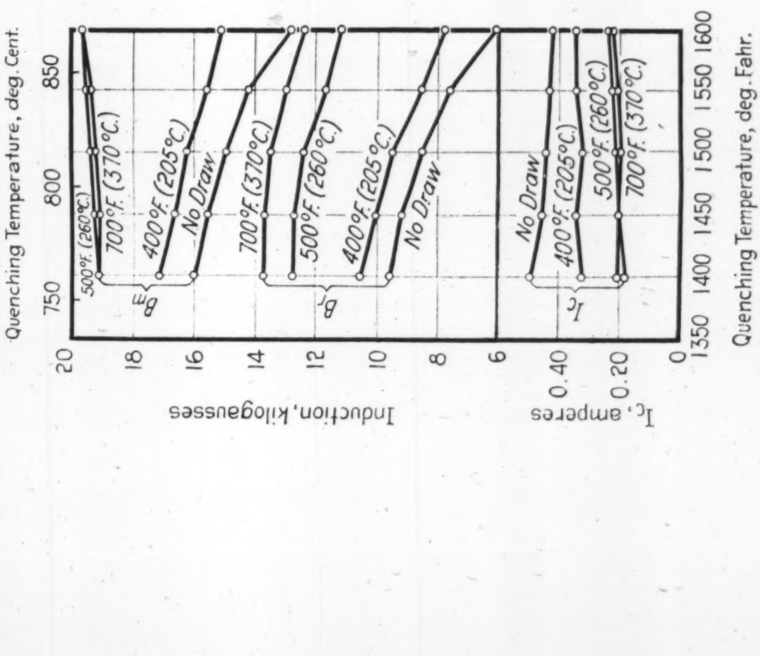


FIG. 12.—Effect of Quenching Temperature on Magnetic Characteristics.

which visible carbide nodules are beginning to separate. The shrinkage of the martensite areas leaves at their boundaries carbon-poor areas which rapidly etch dark. These dark areas grow in size with increasing tempering temperatures and appear to be the beginning of the formation of a ferrite matrix.

Analysis of the Magnetic Properties:

Figure 12 shows graphically the relation between the observed magnetic characteristics and the quenching temperature for the undrawn specimens and those tempered at temperatures of 400, 500, and 700° F. (205, 260, and 370° C.). The curves for other tempering temperatures lie in intermediate positions and are of similar nature. It is of particular interest to note the regular variation of magnetic characteristics with quenching temperature.

The effect of tempering temperature is more clearly shown in Fig. 13 in which the observed magnetic characteristics are plotted against tempering temperature for three different quenching temperatures. These curves represent the typical behavior of carbon steel. B_m and B_r show a marked increase for tempering temperatures between 300 and 500° F. (150 and 260° C.), while the values of I_c show a corresponding decrease.

The thermomagnetic data are of considerable interest because of the light they shed on the tempering process. There are many points to be cleared up before the data of thermomagnetic analysis can be interpreted with certainty, but it appears that this method has much to offer in connection with the study of the phenomena associated with the heat treatment of steel. As the quenching temperatures employed are all below the A_{cm} point, complete solution of the carbide was not obtained. This is shown by the presence of the thermomagentic A_0 transformation. This transformation is not ordinarily observed in quenched hypo-eutectoid steels. The changes due to tempering at different temperatures are mirrored in the thermomagnetic analysis curve.

The magnetic effect of tempering at 200° F. (95° C.) appears to be of a temporary nature. The magnetization rises about one per cent at the tempering temperature but does not change during the half hour of holding at temperature and returns to the original value upon cooling. Upon holding at 300° F. (150° C.) the magnetization increases about one and a half per cent. This increase persists upon cooling. It appears that some definite and irreversible change in the material has taken place. When the specimen is held a half hour at 390° F. (200° C.), a still greater increase in the magnetization is observed amounting to about 7 per cent, most of which is retained upon cooling. As cooling starts, there is an initial increase in magnetization, probably due to the carbide. There is some doubt as to the cause of the increase upon holding at 400° F. (205° C.), but Ellinger[1] attributes it mainly to the release of stress. In a hypoeutectoid steel held at this temperature, there is no indication of an A_0 transformation on cooling which has been taken to indicate that no carbide was formed at this temperature.

Holding at 500° F. (260° C.) produces an increase in magnetization of nearly 30 per cent. This may be attributed to the transformation of the nonmagnetic gamma iron retained as austenite upon quenching to the magnetic alpha iron. A certain amount of carbide may also be formed at this temperature. This would be indicated by the increase in magnetization upon cooling from above the A_0 temperature. This increase amounted to approximately 12 per cent. At 600° F. (315° C.) and 700° F. (370° C.) a decrease in magnetization occurs upon holding at temperature for a half hour. The decreases of 7 per cent and 2 per cent, respectively, probably result from the formation of cementite which is nonmagnetic at these temperatures. This is further indicated by the greatly increased A_0 transformation upon cooling.

CORRELATION OF MAGNETIC AND MECHANICAL PROPERTIES

In this investigation, six materially different physical properties have been measured, three of which were mechanical and three magnetic. An outstanding conclusion drawn from the results is that each property has its own individuality which is distinct from that of the other properties. Relationships between the several properties are not always obvious and when they do appear to exist, it may be for only a limited range of heat treatments. This behavior indicates that the changes taking place in the constitution of the steel during the heat treatments employed are very complex in their nature.

An attempt was made to discover what relationships might exist between any of the observed magnetic characteristics and any of the mechanical properties without regard to the heat treatment by which the properties were developed. This was done by plotting the values obtained in the mechanical tests against the corresponding values obtained in the magnetic tests. As has been experienced in other attempts of a similar nature, with the possible exception of the work reported by Gebert[1], no definite relationships were discovered in this way. As usual, certain quite definite trends were found, particularly in the relationship between hardness and the coercive force. The data, however, do not furnish any practical basis for the prediction of the mechanical properties of a given specimen solely from a knowledge of its magnetic characteristics because there is too great a scatter in the plotted points. This cannot be properly attributed to experimental error, since close agreement was found between the results for all specimens given the same treatment.

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[1] G. A. Ellinger, "Thermomagnetic Investigation of Tempering of Quenched 0.75 per cent Carbon Steel," U. S. Bureau of Standards *Journal of Research*, Vol. 7, p. 441 (1931).

The limitations of space do not permit showing the results of plotting the data as indicated above, but the situation can be appreciated by reference to the curves given in Figs. 4 to 9 and 12 and 13. It is to be noted that the maxima in the curves of mechanical properties have no counterpart in any of the curves of magnetic properties. Furthermore, for tempering temperatures of 500° F. (260° C.) and above, there is practically no differentiation in terms of magnetic characteristics, although there is considerable variation in all of the observed mechanical characteristics. On the other hand, the pronounced variations in magnetic properties in the range of tempering temperatures between 300 and 500° F. (150 and 260° C.) have no counterpart in the curves of mechanical characteristics.

Although the establishment of relationships by means of which mechanical properties could be estimated in terms of data on the magnetic properties is greatly to be desired, the lack of such relationships should not be interpreted to mean that the methods of magnetic analysis have no practical value. The erratic hardening of the first lot of specimens, due to the quenching speed being too slow, was promptly discovered by variations in the magnetic properties and the nature of the difficulty was afterwards confirmed by the results of mechanical and microscopic tests. Such results clearly demonstrate the value of magnetic analysis for controlling uniformity of product. For materials of the same composition and subjected to a treatment known to yield the desired results under normal conditions, variations in magnetic properties exceeding a certain experimentally determined tolerance can surely be taken to indicate unsatisfactory mechanical quality. A very valuable inspection method capable of application at each stage in the process of manufacture is thus afforded. It is only necessary to determine the most convenient magnetic criterion and to design apparatus adapted to the size and shape of the article to be tested. This should be done with a full knowledge of the limitations of the method, as it appears possible that quite appreciable variations in certain regions of tempering temperatures might not be detected by the magnetic tests. Several such applications are in successful operation at the present time.

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[1] N. J. Gebert, "A Systematic Investigation of the Correlation of the Magnetic and Mechanical Properties of Steel," *Proceedings*, Am. Soc. Testing Mats., Vol. XIX, Part II, p. 117 (1919).

Magnetic analysis bids fair to be even more valuable as a tool in the hands of the investigator in the field of metallurgical research. The phenomena associated with the heat treatment of steel can be closely followed by means of non-destructive magnetic tests. A considerable amount of investigation will be necessary in order to establish reliable criteria for the interpretation of the results of thermomagnetic analysis, but this method of investigation has already been of service in the study of the tempering of simple carbon steel and its use could very profitably be extended.

THE TESTING OF ROPE WIRE AND WIRE ROPE

By A. V. de Forest[1] and L. W. Hopkins[2]

Synopsis

Wire rope is probably subject to more abuse and less discrimination in the field than any other accurately designed and constructed mechanism. For this reason, accurate prediction of rope life on the basis of laboratory tests is often disappointing. Service records show, however, that the general level of rope performance is raised by the improvement of the component materials. This improvement can best be effected by the application of suitable test methods for the measurement of quality evolution.

The development of such test methods has in itself been the subject of considerable research here and abroad. This paper describes a few of the methods applied to wire and wire rope by the authors, and typical applications of the resultant test data.

The structural engineer is in the habit of dealing with relatively low unit stresses and rigid structures. The gross stresses can be computed with reasonable accuracy and within fairly close limits. Safety factors can be more or less economically introduced to cover the unknowns. The materials used are of the type having high damping characteristics and the sum of static and dynamic stresses is usually kept well below the endurance limit. The structural engineer will not hesitate, however, to swing a load of girders over a busy street by means of a wire rope in which the tension stresses total one-fourth of the breaking strength, and the bending stresses total one-half of the breaking strength. Acceleration and retardation stresses may easily account for another 5 or 10 per cent. In spite of the high operating stresses, few serious accidents occur. This condition is no mean accomplishment on the part of the rope engineer. The use of adequate test methods applicable to wire and rope serve as a measure of his success, and a basis for improvement.

The testing of wire and rope in relation to useful service is by no means simple, as the rather extensive work by manufacturers and technical societies indicates.[3, 4, 5, 6, 7] The divergence of opinion[1] as to the interpretation of results and the absence of tests embracing the fatigue properties of wire led to the development of test methods and the following investigations.

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[1] Consulting Engineer, American Cable Co., Inc., Bridgeport, Conn.

[2] Materials Engineer, Page Steel and Wire Co., Bridgeport, Conn.

[3] Walter A. Scoble, First, Second, Third and Fourth Reports of the Wire Rope Research Committee, *Proceedings*, Inst. Mechanical Engrs. (British), October, 1920, p. 835; December, 1924, p. 1193; April, 1928; and June, 1930.

[4] R. Woernle, *Zeitschrift des Vereines Deutscher Ingenieure*, Vol. 73, p. 417 (1929); Vol. 74, p. 1417 (1930); Vol. 75, p. 1485 (1931).

[5] G. Sachs and Sieglerschmidt, *Metallwirtschaft*, Vol. 8, p. 129 (1929); *Mitteilungen der Deutschen Materialprüfungsanstalten*, Vol. 10, p. 68 (1930).

[6] A. Pomp, C. Duckwitz, and A. Lindeberg, *Jernkontorets Annaler*, No. 8, p. 371 (1931).

[7] Arthur F. Johnson, Bibliography prepared for the Engineering Foundation, April, 1929.

TESTING OF ROPE WIRE

The inspection testing of rope wire is mostly limited to the determination of gage, breaking strength, number of 90-deg. reverse bends before failure, and the number of 360-deg. twists or torsions in a unit length (usually equivalent to 100 wire diameters) before failure. Endurance tests of rope wire have hitherto not been successful but the fatigue properties of the wire must form a most important part of the general problem. The requirements of an endurance test may be summarized as follows:

1. The point of maximum stress should be at the original cold-worked wire surface.
2. The stressed portion of the specimen should be of maximum length.
3. The stress frequency should be high.
4. The necessity of using a machine straightened specimen should be eliminated.

For wire of uniform rigidity and reasonable straightness, the method employed by Shelton[2] can be used, although it is somewhat slow due to the necessity of operating at speeds below the critical period of the specimen. High tensile strength wire of small diameter finished on a draw block is not straight, and it cannot be straightened without considerably changing the elastic characteristics. The elimination of stress concentration at the grips offers a problem which has baffled most investigators working on fatigue of wire under repeated bending and tension.

The following testing method and procedure was finally developed for studying the fatigue properties of rope wire. The rotating cantilever beam principle is used in the machine design. The specimen is rotated axially and subjected to a constant deflection or bending moment. Cyclic stress reversals from a maximum in compression through zero to a maximum in tension are thus produced. The deflection is maintained by leading the specimen in axial alignment from a motor driven chuck over a 90-deg. sector of a grooved sheave to a freely rotating chuck. A load is applied to the specimen through a thrust bearing incorporated in the freely rotating chuck. The load is adjusted to be just sufficient to modify the vibratory stresses set up by the whipping of the wire at ends not in contact with the sheave. This whipping action concentrates at the chuck jaws and if too severe, causes breakage at this point. The sheave is rotated away from the driven chuck at a speed of 2 to 5 r.p.m. This sheave movement provides for uniform groove wear, simplifies the lubrication problem, reduces the torsional stresses set up by friction and prevents the formation of minute circumferential scratches. The sheaves are a cast tin bearing bronze or cast aluminum alloys of the heat treated aluminum-copper-silicon (No. 195–16) and aluminum-magnesium (No. 197–57) type. Either type of material gives equally good results. The bottom of the sheave grooves has bearing radii of approximately one wire diameter.

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[1] H. L. Whittemore, "The Need of Research on Wire Rope," paper prepared for the Wire Rope Research Committee, Am. Soc. Mechanical Engrs., April, 1929.

[2] S. M. Shelton, "Fatigue Testing of Wire," *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part II, p. 204 (1931).

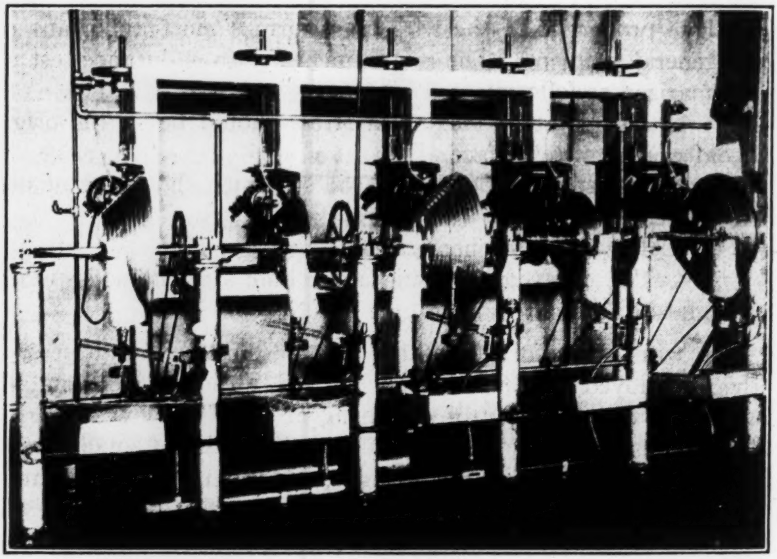

FIG. 1.—Fatigue Testing Apparatus for Rope Wire.

A high-grade motor oil saturated with collodial graphite is continuously supplied to the sheave and is recirculated through a filtering system. Small drill chucks are mounted on direct-current motor spindles. The specimen is rotated on its axis at 3000 r.p.m. Lubrication troubles and maintenance costs are kept at a minimum at this speed. Tests have been successfully run at speeds of 12,000 r.p.m. and bending stresses of 125,000 lb. per sq. in., but lubrication difficulties multiply at excessive speeds resulting in wear of the specimen and sheave. The motors are equipped with Veeder pick counters driven by worm reduction gears with 1000:1 ratio. Contacts in the motor circuit are opened by the movement of the free chuck upon failure of the specimen. Facilities are provided for the rapid alignment of the wire specimen with the sheave groove. Anti-friction bearings are used throughout to insure smooth operation. The machine is illustrated by Figs. 1 and 2.

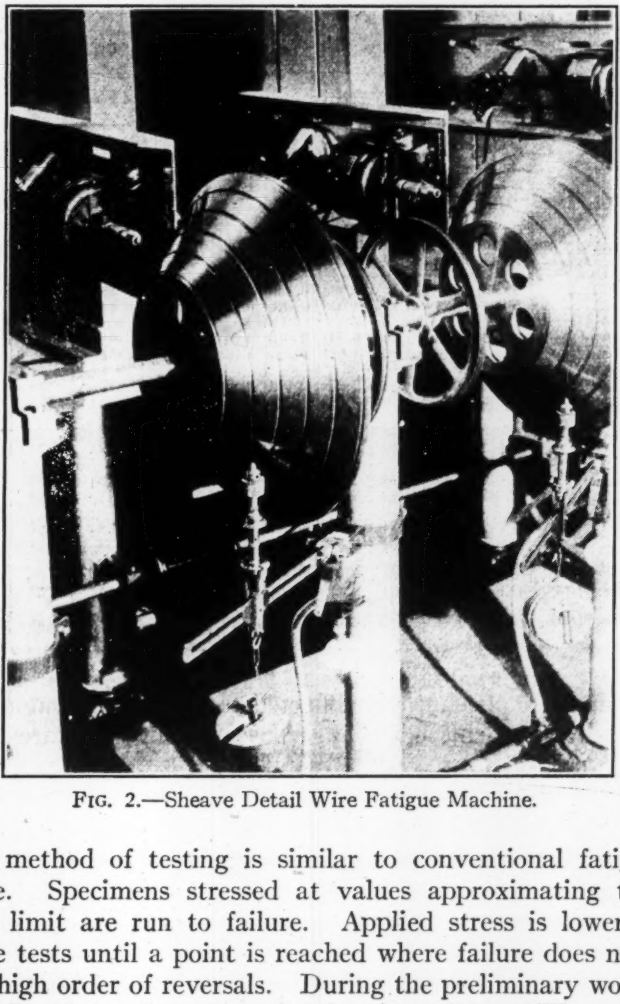

FIG. 2.—Sheave Detail Wire Fatigue Machine.

The method of testing is similar to conventional fatigue test procedure. Specimens stressed at values approximating the proportional limit are run to failure. Applied stress is lowered with successive tests until a point is reached where failure does not occur within a high order of reversals. During the preliminary work, tests were continued to the conventional value of 10 million reversals. The endurance limit was arbitrarily set at the point where an increase in 2000 lb. per sq. in. fiber stress resulted in a decrease of 100,000 reversals. At this point the cyclic-stress curve is, for practical purposes, a horizontal line and the order of reversals is between 500,000 and 1,500,000 for most wire. This fact, substantiated by rope tests and service records of ropes subject to high bending stresses indicated the questionable value of continuing fatigue tests on rope wire beyond 2,000,000 reversals. The so-called endurance limit is, of course, arbitrary but is within the limits of reason for rope wire.

TABLE I.—WIRE SELECTED FOR PRELIMINARY ENDURANCE TESTS.

Group	Type	Diameter, in.	Chemical Properties, per cent					Physical Properties			Endurance Data	
			Carbon	Manganese	Sulfur	Phosphorus	Silicon	Tensile Strength, lb. per sq. in.	Torsions in 100 Diameters	90-deg. Reversed Bends	Endurance Limit, lb. per sq. in.	Endurance Ratio
No. 1.	Iron............	0.043	0.04	0.18	0.021	0.006	0.005	85 400	5 to 87	100	51 000	60
No. 2.	Iron............	0.043	0.03	0.29	0.028	0.034	0.004	98 000	76	90	53 000	54
No. 3.	Iron............	0.043	0.07	0.41	0.034	0.043	0.003	89 500	55	108	56 000	63
No. 4.	Iron............	0.043	0.06	0.36	0.033	0.029	0.001	85 500	94	86	54 000	63
No. 5.	Toughened steel .	0.045	0.22	0.44	0.024	0.014	0.07	140 000	41	58	71 000	51
No. 6.	Toughened steel .	0.045	0.36	0.80	0.027	0.011	0.004	158 500	34	86	71 000	45
No. 7.	Toughened steel .	0.045	0.37	0.84	0.034	0.014	0.003	158 500	27	78	71 000	45
No. 8.	Cast steel	0.040	0.38	0.56	0.049	0.036	0.15	206 800	43	114	82 000	40
No. 9.	Cast steel	0.043	0.41	0.58	0.031	0.015	0.19	201 100	44	88	91 000	45
No. 10	Cast steel	0.043	0.41	0.59	0.030	0.013	0.17	219 700	29	72	69 000	32
No. 11	Mild plow	0.040	0.59	0.64	0.027	0.012	0.17	214 800	33	52	73 000	34
No. 12	Plow...........	0.043	0.68	0.49	0.032	0.012	0.26	239 700	41	90	71 000	30
No. 13	Plow...........	0.040	0.72	0.54	0.024	0.023	0.16	275 300	38	64	105 000	38
No. 14	Plow...........	0.040	0.72	0.54	0.025	0.022	0.16	284 800	33	74	102 000	36
No. 15	Improved plow ..	0.040	0.73	0.51	0.021	0.011	0.21	278 400	38	66	86 000	31
No. 16	Improved plow ..	0.045	0.71	0.41	0.029	0.022	0.14	284 300	34	84	89 000	31
No. 17	Improved plow ..	0.045	0.76	0.41	0.029	0.021	0.13	283 000	31	86	75 000	26

As the wire specimen is deflected to a constant value of strain, stress must be calculated. The conventional curvature formula is used:

$$f_s = \frac{\frac{d}{2}E}{R} + \frac{P}{\pi \frac{d^2}{4}}$$

where f_s = maximum unit fiber stress,
d = diameter of wire,
E = modulus of elasticity, 29,000,000 for steel wire,
R = radius of test sheave from axis to center of the wire,
P = tension on wire, in pounds.

Preliminary tests made with this equipment included a variety of types of rope wire, the characteristics of which are given in Table I.

Figure 3 shows some typical fatigue curves. This test has proved of value in correlating the various elements of processing with a practical measure of quality. Changes in annealing, patenting, and drafting practices have been made and the resultant improvements verified by fatigue tests.

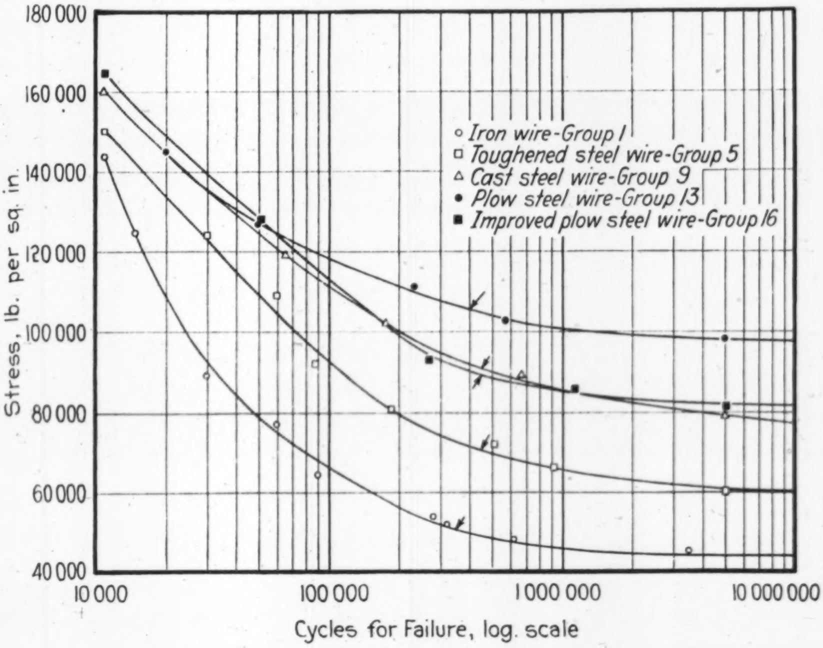

FIG. 3.—Showing Typical Cyclic-Stress Diagrams for Rope Wire.

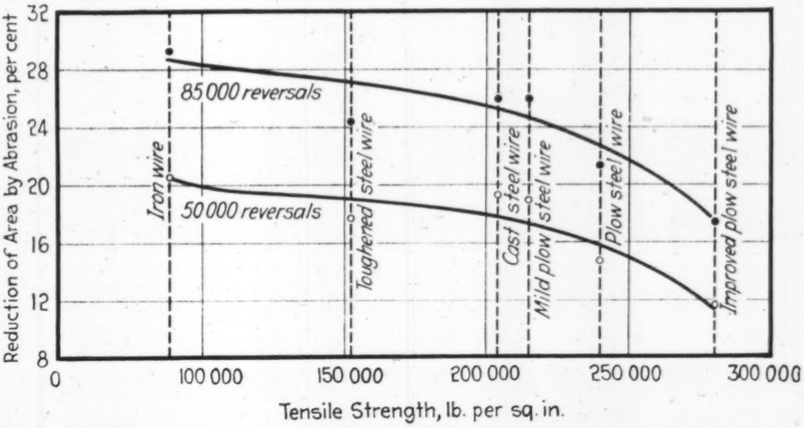

FIG. 4.—Showing Relation of Tensile Strength to Abrasion Resistance of Rope Wire.

An example of the practical application of endurance data to rope engineering may be of interest.

It was found that two lots of wire acceptable under the specifications for inclusion in the same grade had a difference in endurance limit of 12 per cent. Assuming a hypothetical rope of $\frac{5}{8}$-in. 6 × 19 Warrington Construction operating safety factor of 4 to 1, rope made from wire A can be operated over a 23-in. sheave, but for equal life, rope made from wire B must be operated over a 29-in. sheave. Expressed differently, the two ropes would have a theoretical difference in life of 40 per cent when used over 23-in. sheaves.

An interesting adaptation of the fatigue test method described above to the measurement of abrasion resistance of wire has been worked out and a few tests run. The equipment is essentially the same except that the test sheaves are chilled cast iron. A mixture of oil and emery is fed to the point of contact between wire and sheave. The specimen is rotated at about 1800 r.p.m.; the sheave at 2 r.p.m., and wear of the wire specimen takes place. The test is continued to some predetermined value of reversals known to be under the endurance limit. The wire is then removed and gaged. A few studies were made of the rate of wear of differently processed wire. The results are encouraging but not conclusive. Figure 4 shows the general relation of tensile strength and abrasion resistance irrespective of processing or analysis.

TESTING OF WIRE ROPE

The properties of wire rope of most interest to the user are strength, flexibility, elasticity, resistance to wear or abrasion, rate of deterioration due to bending, and corrosion. The determination of breaking strength and elastic properties of rope is preceded by careful preparation of specimens. The gage length of specimen is usually equal to approximately 10 rope lays. The wires are unlayed or "bushed" at each end, cleaned with gasoline and acid, and inserted in a standard type of wire rope socket having a cone shaped basket. Molten zinc is then poured around the wires. The equalization of load to each wire and strand during testing is in direct proportion to the care and skill used in the socketing operation. Ropes tested to destruction should fail in at least 50 per cent of the strands simultaneously. Single strand breaks usually occur because of poor socketing or deficient rope making.

The measurement of elastic strain is done with special extensometers having a gage length of approximately 3 ft. and arranged to compensate for the relatively high torsion which takes place on application of load. The determination of elastic modulus is made on pre-stressed specimens. The amount of pre-stressing necessary to obtain a consistent stress-strain relation is dependent upon the compressibility of the core, the diameter of the core, the radial pressure applied to the strands during the manufacture of the rope, and the internal stresses present. Ropes are usually pre-stressed to the working load before determining the elastic constants. The life of a rope may be divided into three periods during which it undergoes changes in elastic behavior. During the first period the stress-strain relation changes rapidly. This represents the gradual seating of strands into the core. During the second period, the stress-strain

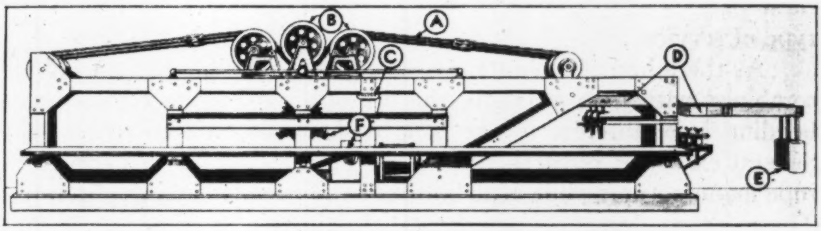

FIG. 5.—Fatigue Testing Apparatus for Wire Rope.

The test specimens, *A*, reaved around the test sheaves, *B*, and reciprocated by the mechanism, *F*, thus subjecting the ropes to reverse bends. The proper rope tension is maintained at all times by means of the compound lever system, *D*, and weight, *E*. Cycles of reverse bends are recorded by counter, *C*.

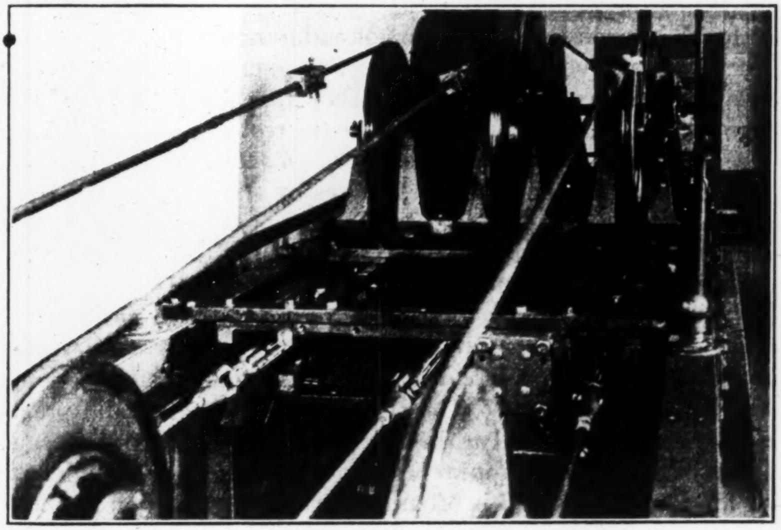

FIG. 6.—Sheave Detail Rope Testing Machine.

relation remains reasonably constant, as the strands become firmly seated and concentrically spaced. During the third period, usually accompanied by the development of wire failures, the rope is "dead," and the strands locked together, it has relatively less elasticity and consequently less ability to absorb shock loads. The definiteness of these periods is, of course, dependent upon the character of rope and type of service.

As the inherent advantage of using wire rope lies in its flexibility combined with high strength, the life of a rope subject to alternate bending is of interest to the rope designer as well as to the user. Several extended researches have been conducted on this subject by rope manufacturers, but little information is available in the literature. The work conducted by the British Institution of Mechanical Engineers[1] and Dr. Woernle[2] are by far the most comprehensive researches reported. Neither group has concluded its work.

An ideal endurance test for wire rope should permit the application of the combined stresses of bending, tension and torsion to the specimen in the desired ratio. Many test methods have been developed for this purpose. Eight years of endurance testing have resulted in the gradual evolution of the testing equipment illustrated by Fig. 5. The sheave arrangement is shown in better detail in Fig. 6. The rope is passed back and forth over the test sheaves and subjected to 6 reversals of bending stress per cycle. Constant tension is applied to the specimen through the end sheaves by a lever weighing system. The specimen is twisted, held neutral, or untwisted at the end fastenings and held in position or rotated as desired. Under ordinary conditions of testing, bending stresses are applied in one plane only.

Test procedure involves keeping a record of the cycles of bending stress, determining the stretch of the rope at increments of reversals and the deterioration as evidenced by the number of broken wires in the individual strands. The end point of the test, as in practical use, is usually considered to be the point at which a predetermined number of wire breaks appear within one foot. This unit length is used for convenience and is often converted to a function of the rope lay for comparative purposes. Occasionally tests are continued to complete failure. The ratio of breaks per rope lay to breaks in the full length of specimen subject to bending stress is of interest in indicating probable life in service under applications of suddenly applied load. After the test is completed the rope is completely

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[1] Walter A. Scoble, First, Second, Third and Fourth Reports of the Wire Rope Research Committee, *Proceedings*, Inst. Mechanical Engrs. (British), October, 1920, p. 835; December, 1924, p. 1193; April, 1928; and June, 1930.

[2] R. Woernle, *Zeitschrift des Vereines Deutscher Ingenieure*, Vol. 73, p. 417 (1929); Vol. 74, p. 1417 (1930); Vol. 75, p. 1485 (1931)

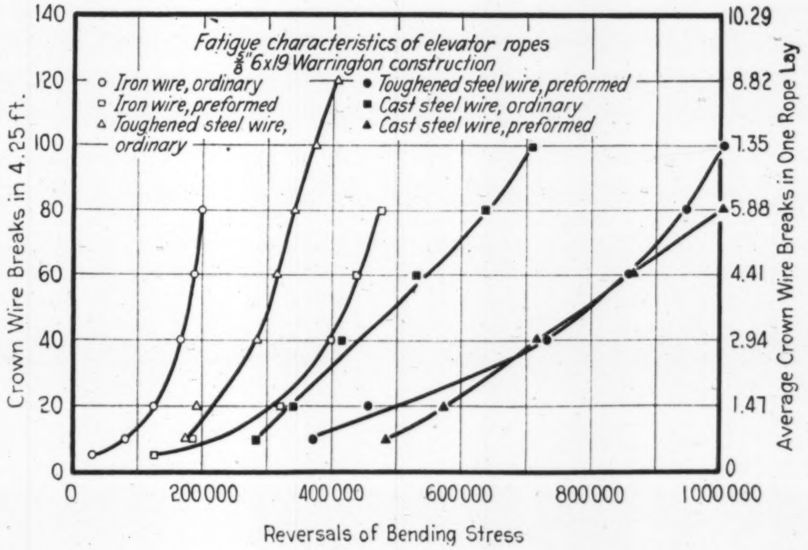

FIG. 7.—Fatigue Life Characteristics of Elevator Ropes, Preformed and Non Preformed, Made of Different Materials.

Sheave Diameter=32 rope diameters. Load in tension=5 per cent of breaking strength. All tests discontinued at 13 crown wire breaks per lay.

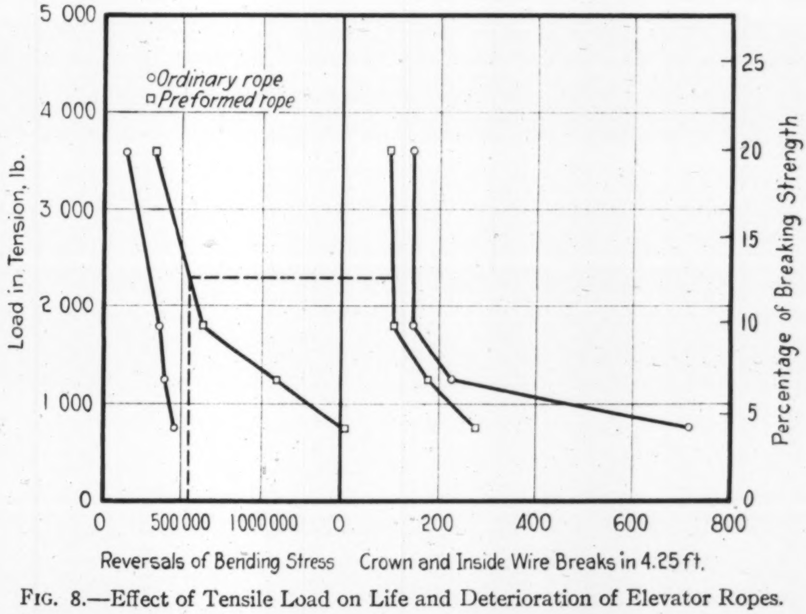

FIG. 8.—Effect of Tensile Load on Life and Deterioration of Elevator Ropes.

Effect of tensile load on life and deterioration of traction steel elevator rope. Sheave diameter = 32 rope diameters. All tests discontinued at 13 crown wire breaks per rope lay.

dissected and a *post mortem* analysis made of its condition. All wire breaks are recorded in relation to their location in the strand and in the rope and the condition of the core is noted. Wire breaks are classified as follows:

Crown Wire Breaks.—Breaks visible on the outer strand crowns.

Valley Breaks.—Breaks occurring at a point adjacent to strand contact accompanied by wire nicks and usually caused by core collapse or inadequate core.

Inside Breaks.—Breaks occurring on the outer series of wires but adjacent to the core, not normally visible.

Inner Wire Breaks.—Breaks occurring in the inner series of wires, not normally visible.

Core Wire Breaks.—Failure of the core or king wire.

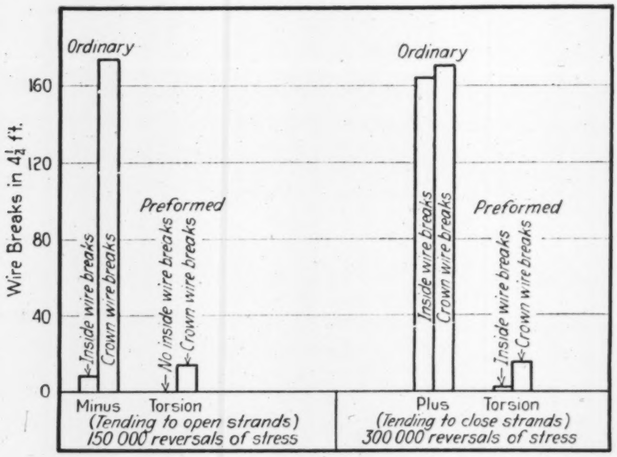

FIG. 9.—Effect of Externally Applied Torsional Stress on the Life and Deterioration of Elevator Ropes.

$\frac{5}{8}$-in. 6 × 19 Warrington toughened steel elevator rope. Sheave diameter = 32 rope diameters. Tension = 10 per cent breaking strength. Applied torsion = ± 4.5 deg. per rope lay.

Occasionally ropes are removed from the fatigue machine at various stages of deterioration and subjected to tension tests to determine the loss in strength. This procedure is in general unsatisfactory, as after the rope is tested the evidence is destroyed. The reserve strength developed by a rope which has a large number of broken wires is largely dependent upon the extent of core collapse and the resultant friction developed between strands, and the rope lay. Proper socketing is also essential.

The relative life-deterioration relationship for ropes made of iron, toughened steel, and cast steel wire is shown in Fig. 7. The effect of preforming on this relationship is also shown.

The effect of varying the tensile load upon the life of traction steel elevator ropes is shown in Fig. 8.

The effect of varying the torsional stress upon the life of traction steel elevator ropes is shown in Fig. 9. It is a common but condemned practice to equalize the length of parallel elevator hoist ropes by twisting or untwisting the ropes during installation. Building managers are then greatly surprised when one or two of the ropes are in much better condition than the remainder when removed. The application of external torsional stress is often a contributing factor.

Another form of testing machine known variously as the "doughnut" or "smoke ring" machine developed for the purpose of subjecting a rope to bending stress with no tension or shear is illustrated in Fig. 10. The rope specimen is formed into an arc of known curvature and having a length of 180 deg. The two ends of the rope are clamped in chucks of the spring collet type which are positively rotated in the same direction and at the same speed. The rope "floats" between chucks with the aid of suitable supports. The type of rope failure obtained on this machine is typical of service failures in installations where the bending stress is high in relation to the tensile stress. Ropes which are not properly designed with respect to wire sizes respond very quickly to this treatment by showing their internal friction in the form of heat.

Woernle has developed a similar machine for rope testing in which the rope is held under tension against a quadrant and rotated axially. Combined bending and tension stresses are thus obtained. No results of tests made on this type of machine are available.

The fatigue testing of small flexible cables such as are used for aircraft control cables is carried on continuously by the War and Navy Departments. The current standard specifications require that a $\frac{1}{8}$-in. 7 × 19 tinned or galvanized control cable develops at least 50 per cent of the original minimum strength after 300,000 reversals around a 1$\frac{3}{8}$-in. pitch diameter sheave. Figure 11 illustrates the type of testing apparatus used for testing this type of cable. This machine was designed by D. A. Warner of the Materiel Division, War Department at Wright Field. The test specimens are reaved around the test sheaves and the large load sheave. The rope ends are fastened to the central drum which oscillates through an arc, thus producing alternate bending and straightening of the specimen. After the machine has produced the required oscillations it stops automatically. The cables are removed and the reserve strength determined by tension tests. The machine is exceptionally smooth in operation due to the light weight of all moving parts.

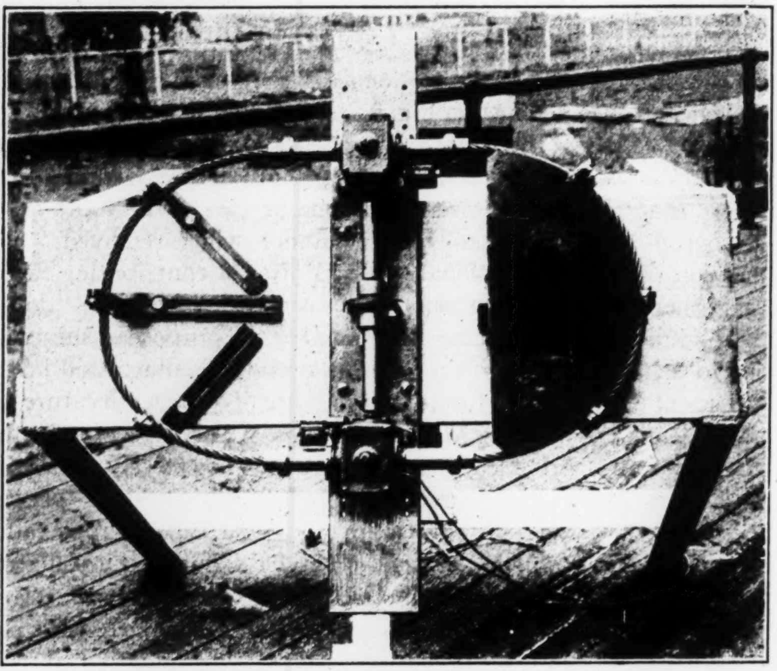

FIG. 10.—"Smoke Ring" Bend Testing Machine for Rope.

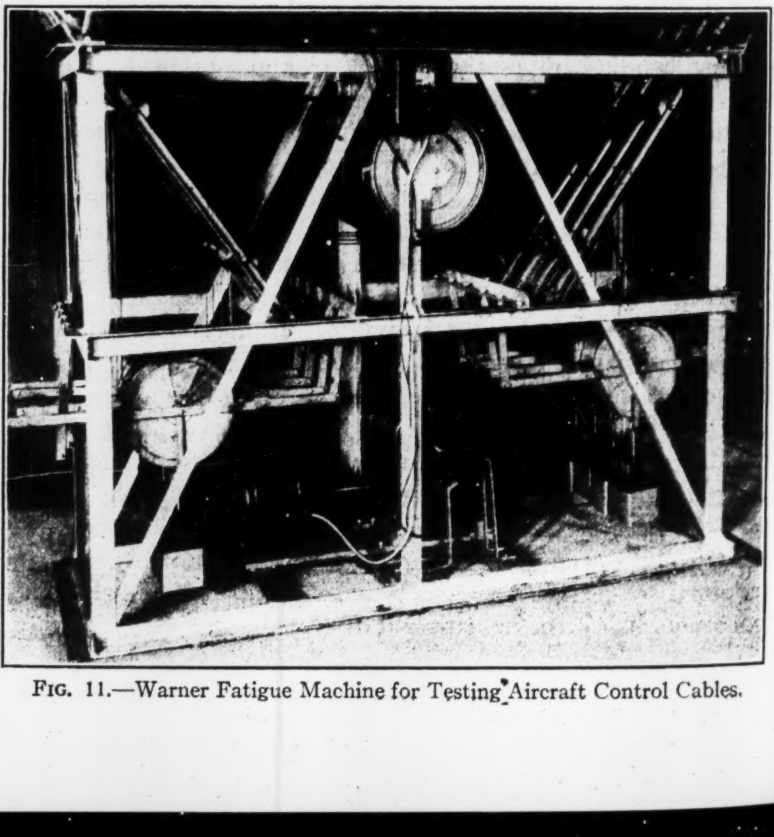

FIG. 11.—Warner Fatigue Machine for Testing Aircraft Control Cables.

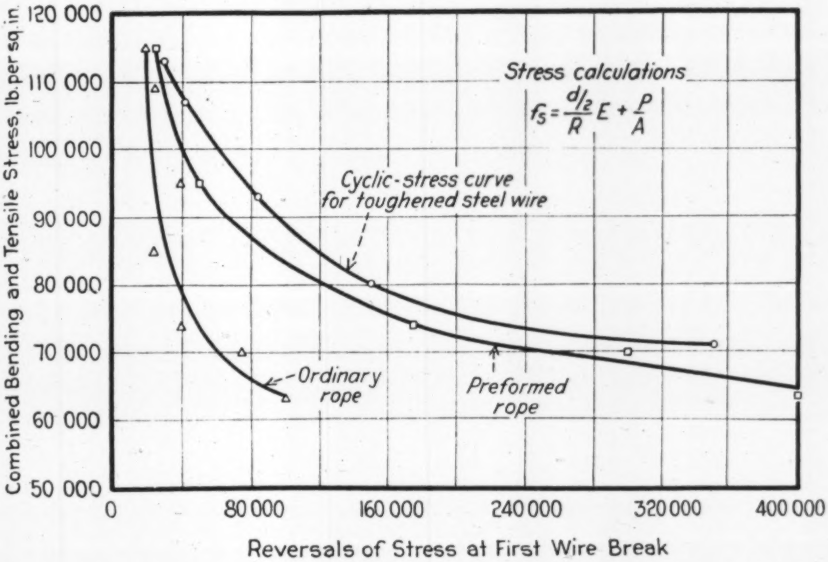

FIG. 12.—Comparison of Endurance Properties of Single Wire with Those of Wire in Rope.

Wire.—Toughened Steel. *Rope.*—$\frac{5}{8}$-in. 6 × 19 Warrington Toughened Steel Elevator Rope.

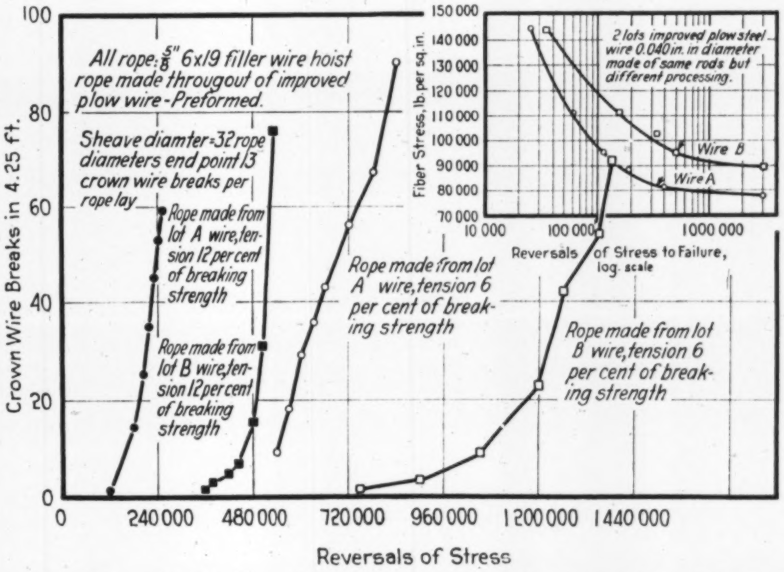

FIG. 13.—Effect of Variation of Processing on Endurance Properties of Wire and Rope.

The correlation of properties of components to the performance of the complete structure is the ultimate aim of all testing. The correlation of fatigue properties of wire to the life of rope in the field is an extremely hazardous undertaking because of the constantly changing conditions, but it is evident that, other things being equal, increasing the fatigue properties of the wire will improve the life of the rope.

An ideal rope should last as long as a single wire when subject to the same bending stress before a single wire fails. Figure 12 shows the effect of preforming on the life of a single wire in a rope as compared with the endurance properties determined on the single wire.

The "life" curves of the preformed rope and single wire are practically parallel whereas the data for the non-preformed rope is erratic and the "life" curve departs considerably from the ideal. These tests were made on toughened steel wire and $\frac{5}{8}$-in. 6 × 19 Warrington toughened steel elevator ropes incorporating the single wire as the large wire in the outer series.

An interesting series of tests has been completed on the correlation of process variations on wire with quality of rope. Figure 13 shows the life-deterioration relation of two ropes made of wire which originated from the same rods but which have been processed differently. Both A and B wires are acceptable under specifications with relation to tensile strength and torsions. The relatively large difference in endurance values of the two wires is reflected in the increase in rope life of 40 to 50 per cent. The wire tests were run on the same wire which was incorporated in the outer series of wires in the ropes—$\frac{5}{8}$-in. 6 × 19 filler wire improved plow preformed hoist ropes.

When subject to bending, a wire rope behaves somewhere between a solid bar of the same outside dimensions and a loose assembly of wires, each acting independently. The degree of friction between the various components is constantly changing during the life of the rope, and, with this variation, the stresses imposed on the wires. In an ordinary rope, the wires in the strand and the strands in the rope are simply sprung into position and held in place by a wrapping at the ends. Both wires and strands are under a continual stress. This may be best seen by cutting a seizing. In preformed rope the components are formed to the shape of the helix they will assume in the finished rope. There is therefore a minimum of internal stress and the strands stay in position relative to the core when the seizing is cut.

A stress analysis which does not take changing conditions and the presence or absence of internal stress into account fails of accurate prediction. Diligent testing and design, accurate manufacture and intelligent application and use in the field are the answer to economic rope life.

FATIGUE OF SHAFTS HAVING KEYWAYS

By R. E. Peterson[1]

Synopsis

This paper presents data on the fatigue of shafts having two kinds of keyways: sled-runner and profiled types. It is shown that the former has a greater fatigue strength. Applications of the data are discussed.

Introduction

Keyed members constitute an important type of machine element about which insufficient fatigue data are available.[2, 3, 4]. The key itself presents no particular fatigue problem. The majority of failures seem to have occurred in the shafting, rather than in the attached pulley, gear or coupling. The primary purpose of keyed shafting is to transmit torque, but in addition to the resulting steady component of shearing stresses, there are usually superimposed alternating shearing stresses (reciprocating engine drives) or alternating bending stresses (gear and pulley drives, particularly with overhung shafting). This paper will concern itself primarily with the latter classification, although the conclusions reached have some bearing also on the former classification.

An important point which has been brought out by the tests herein described is that the keyway end is often an important factor in determining failure. Two types of keyway ends are in common use; the sled-runner type, as cut with an ordinary milling cutter of the same width as the keyway (Fig. 1 (*a*)); and the profiled type, as cut with an end-mill of the same diameter as the width of the keyway (Fig. 1 (*b*)). A service failure of a street car drive shaft having a keyway of the latter type is shown in Fig. 2. As previously indicated, the alternating stresses in an application of this kind are of bending type. Another failure of a shaft having a profiled keyway[1] is shown in Fig. 3. The importance of considering the shape of the keyway end is obvious from Figs. 2 and 3.

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[1] Manager, Mechanics Division, Research Laboratories, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[2] H. J. Gough, "The Effect of Keyways on the Strength and Stiffness of Shafts," *British Aeronautical Commission Reports and Memoirs No. 864* (1925).

[3] For static tests see paper by H. F. Moore, "Effect of Keyways on the Strength of Shafts," *Bulletin No. 42*, University of Illinois Engineering Experiment Station (1909).

[4] For photo-elastic tests see paper by A. G. Solakian and G. B. Karelitz, "Photoelastic Study of Shearing Stresses in Keys and Keyways," presented at the 1931 annual meeting of The American Society of Mechanical Engineers.

TEST RESULTS

The fatigue test specimens were of cantilever type 1 in. in diameter with keyways $\frac{1}{4}$ in. wide and $\frac{1}{8}$ in. deep (Fig. 5). The sled-runner keyways were cut with a $1\frac{1}{2}$-in. diameter cutter. The testing machine has been described previously.[2]

Two materials were tested, the properties being as follows:

	Treatment	Tensile Strength, lb. per sq. in.	Yield Strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of Area, per cent	Hardness, Vickers Penetration Number
Chromium-Nickel Steel: Carbon 0.39, manganese 0.64, nickel 1.25, chromium 0.62, silicon 0.23, sulfur 0.019, phosphorus 0.012 per cent.....	Water quenched at 875° C., tempered at 650° C..	103 500	70 000 (2 per cent of plastic deformation)	25	66	228
Medium Carbon Steel: Carbon 0.45, manganese 0.59, silicon 0.24, sulfur 0.032, phosphorus 0.034 per cent........	Normalized 2 hours at 825° C..	80 000	45 000 (0.2 per cent of plastic deformation)	32	55	160

The fatigue test data are shown graphically in Fig. 4 and the results summarized in Table I. The reason for giving two values of endurance limit is that the (*a*) value is useful for designers and the (*b*) value is of interest to investigators of stress concentration effect. In the case of the (*b*) values with a keyway on one side, it is first necessary to find the position of the center of gravity, as follows:

$$\bar{y} = \frac{\frac{\pi}{8} d^3 - wh\left(d - \frac{h}{2}\right)}{\frac{\pi}{4} d^2 - wh}$$

where d = diameter of shaft,
w = width of keyway, and
h = depth of keyway.

The moment of inertia for a section with a keyway becomes:

$$I = \frac{\pi}{64} d^4 + \frac{\pi}{4} d^2 \left(\frac{d}{2} - \bar{y}\right)^2 - \frac{wh^3}{12} - wh\left(d - \bar{y} - \frac{h}{2}\right)^2$$

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[1] Graf, "Die Dauerfestigkeit der Werkstoffe und der Konstruktionselement," p. 44, Julius Springer, Berlin (1929).

[2] R. E. Peterson, "Fatigue Tests of Large Specimens," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 373 (1929).

The moment of inertia for the case of a transverse hole is:

$$I = \frac{\pi}{64} d^4 - \frac{wd^3}{12}$$

where w = diameter of hole.

The final data of Table I are given in terms of stress concentration factor,[1] defined as:

$$k = \frac{\text{ordinary endurance limit}}{\text{endurance limit with keyway or hole}}$$

Two values of k are also given, corresponding to the (*a*) and (*b*) values of the denominator. Recent tests[2] indicate that fatigue stress concentration factors are not independent of size.

TABLE I.—RESULTS OF TESTS ON TWO TYPES OF STEEL.

	ENDURANCE LIMIT, LB. PER SQ. IN.		STRESS CONCENTRATION FACTOR	
	(*a*) USING SECTION MODULUS I/c FOR SOLID 1-IN. DIAMETER SECTION	(*b*) USING I/c BASED ON NET SECTION ASSUMING LINEAR STRESS DISTRIBUTION	(*a*)	(*b*)
Chromium-Nickel Steel (Heat-Treated)				
No keyways (ordinary tapered specimens)	58 000	.....	....	....
Sled-runner keyways	36 000	42 800	1.61	1.35
Profiled keyways	28 000	33 300	2.07	1.74
Medium-Carbon Steel (Normalized)				
No keyways (ordinary tapered specimens)	37 000	.....	....	....
Sled-runner keyways	28 000	33 300	1.32	1.11
Profield keyways	23 000	27 400	1.61	1.35
¼-in. hole (transverse)	12 100	21 000	3.06	1.76

The location of fracture is shown in Fig. 5. The profiled keyways failed in all cases at points of tangency of the semi-circular ends, the initial direction of cracking being at a slight angle to a normal section of the shaft. It will be noticed that Fig. 2 shows the same kind of fracture. The shaft in Fig. 2 represents an application involving alternating bending stresses and constant torque. It was thought that perhaps the torque would have some effect on the direction of cracking. A medium-carbon steel specimen (profiled keyway)[3] was run at a constant torque corresponding to a shearing

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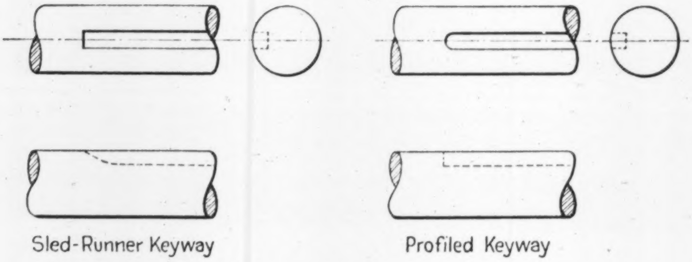
[1] Report of Research Committee on Fatigue of Metals, Appendix: "Present-Day Experimental Knowledge and Theories of Fatigue Phenomena in Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part I, p. 298 (1930).

[2] See paper by R. E. Peterson, "Model Testing as Applied to Strength of Materials," presented at the meeting of The American Society of Mechanical Engineers in Bigwin, Canada, June 29, 1932.

[3] Test specimen had previously completed 12,000,000 cycles (below endurance limit).


Sled-Runner Keyway

Profiled Keyway

FIG. 1.—Types of Keyway Investigated.

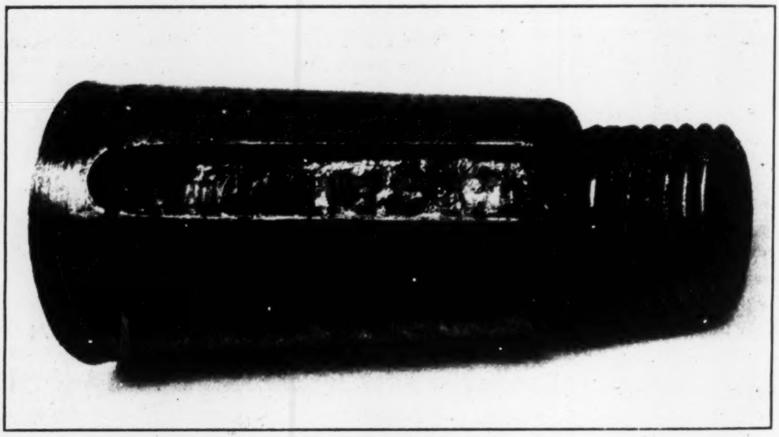


FIG. 2.—Service Failure at Keyway.

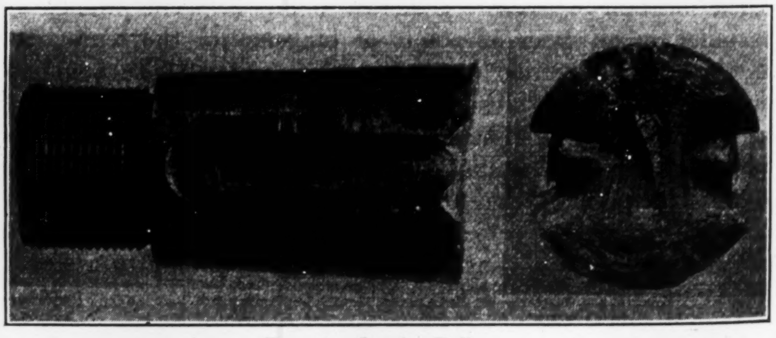


FIG. 3.—Service Failure.

Graf, "Die Dauerfestigkeit der Werkstoffe" und der Konstruktionselement, Julirus Springer, Berlin (1929).

stress of 11,000 lb. per sq. in. and a simultaneous alternating stress of 45,000 lb. per sq. in. The position and direction of initial cracking was the same as for the specimens without the constant torque.[1]

From Fig. 5 it will be noticed that the sled-runner keyway did not break at the extreme end of the keyway. The distance from the end varied, being greater in the chromium-nickel steel shafts than in the medium-carbon steel shafts (average 0.30 in. as compared with 0.05 in.). A chromium-nickel steel specimen which had not broken in 10,000,000 cycles was run at a higher stress and developed cracks in two places (0.05 in. and 0.40 in. from the end). In all cases observed the crack started at the outside edge, never at the bottom

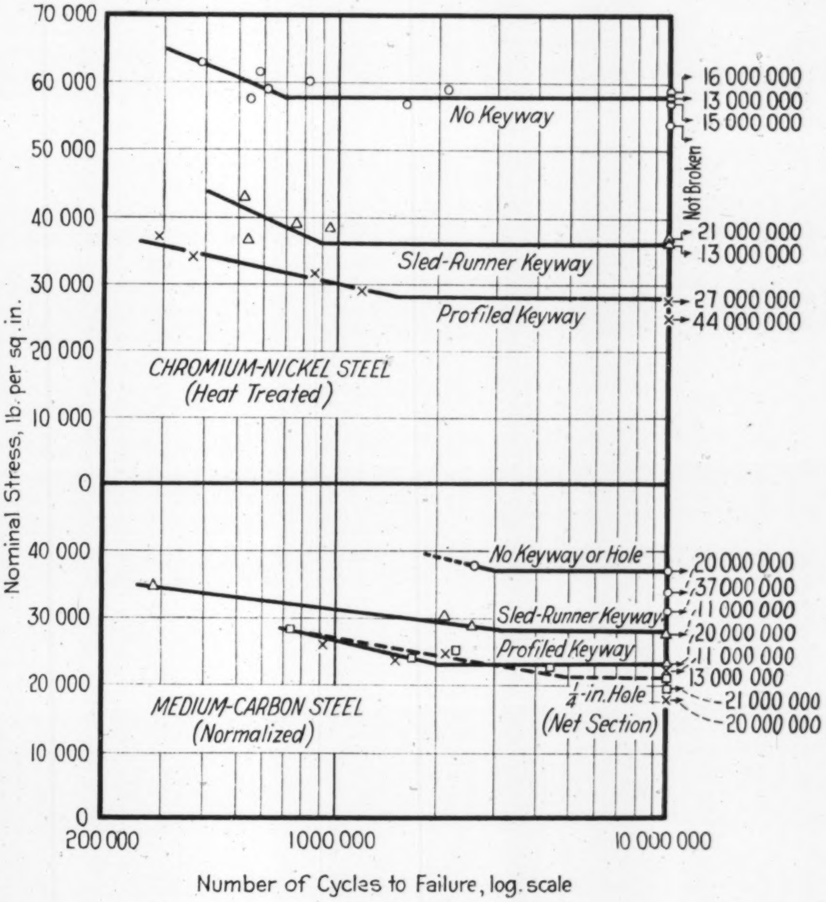


FIG. 4.—Fatigue Test Data.

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[1] See paper by F. C. Lea (Sheffield), "Effect of Alternating Bending Plus Steady Torsion," *Engineering* (London), August 20, 1926.

of the keyway. Just why the crack should start at different distances from the end of a sled-runner keyway is not clear. Unfortunately, the stress distribution at the end of a sled-runner keyway is not known. This is a three-dimensional stress problem and cannot be solved photo-elastically. A rubber model may offer possibilities in obtaining an approximate solution.[1]

Since the end of a profiled keyway is somewhat similar to a transverse hole from the standpoint of stressing, comparative tests were made with medium-carbon steel. The stress concentration factors given in Table I—1.35 for profiled keyway, and 1.76 for the hole (both based on net section)—show that there is a considerable difference between the two cases. It was expected that the hole would represent a more severe case, but a smaller difference was anticipated. The above test indicates that the available data in the literature on the effect of holes in fatigue may be safely used in the design of profiled keyways.

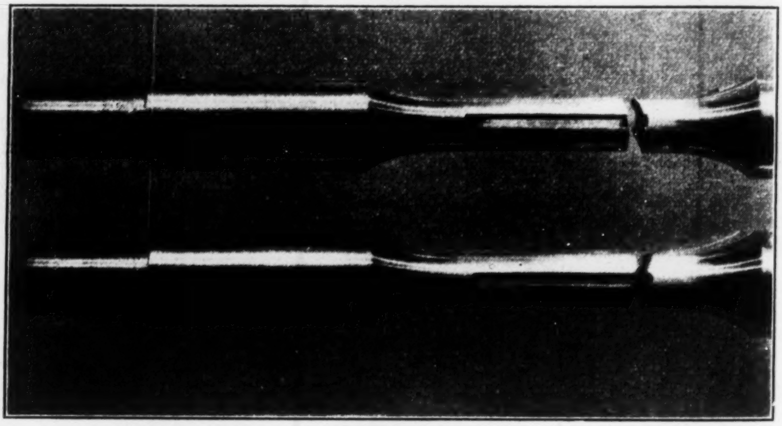

FIG. 5.—Fractured Specimens.
Top—Sled-runner keyway.
Bottom—Profiled keyway.

As stated in the introduction, shafts having keyways are sometimes subjected to alternating torsion, as in the case of reciprocating engines. Researches of Ludwik[2] show that the ratio between torsion and tension yield points, 0.575, holds also for endurance limits ± 6 per cent and further that the same relationship holds for torsion and bending fatigue tests involving stress concentration. This means that for the cases investigated the stress concentration factors were the same for bending and torsion. Until further data are available, the factors given in Table I might consequently be used in design for both bending and torsional fatigue applications.

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[1] H. Stoll, "Die Eignung von Weichgummi zum experimentallen Ermittlung von Spannungsbildern," *Forschung*, Vol. 2, p. 313 (1931).

[2] P. Ludwik, "Kerb- und Korrosiondauerfestigkeit," *Metallwirtschaft-Metallwissenschaft-Metalltechnik*, Vol. 10, p. 708 (1931).

The data of Table I should prove useful to engineers in setting up design codes. The following is quoted from the Code for Design of Transmission Shafting.[1] "The high localized stresses set up in the vicinity of a keyway cut in a shaft are emphasized by shock and fatigue and either of these will cause localized failure at much lower loads than indicated by static tests. To insure an adequate safety factor in the design of a shaft with standard keyway it is tentatively recommended that such a shaft be designed on the basis of a solid circular shaft using not more than 75 per cent of the working stress recommended for the solid shaft." From the data of Table I it is seen that the fatigue strength of a shaft having a keyway may be considerably less than 75 per cent that of a solid section, being as low as 48 per cent in the case of the profiled keyway in chromium-nickel shafting.

CONCLUSIONS

1. The sled-runner type of keyway is preferable to the profiled type from the standpoint of fatigue. The former has an endurance limit (bending) 22 per cent higher for medium-carbon steel and 29 per cent higher for chromium-nickel steel (heat-treated), the specimens being 1 in. in diameter.
2. The profiled keyways failed at the points of tangency of the semi-circular end. Superimposed constant torque did not change the position or direction of fatigue cracking.
3. Tests of specimens having transverse holes $\frac{1}{4}$ in. in diameter showed a lower endurance limit than the profiled keyway, when compared on the basis of net section.
4. The sled-runner keyways did not fail at the extreme end of the keyway, the distance from the end varying from 0.05 to 0.40 in.
5. Published data indicate that the stress concentration factors obtained in bending can be used for torsional cases, at least until further results are available.

Acknowledgments.—Acknowledgment is due Mr. L. W. Chubb, Director of the Westinghouse Research Laboratories, for permission to publish these results. The author is indebted to Mr. F. Cassel for carrying out the test program.

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[1] Code for Design of Transmission Shafting, Am. Soc. Mechanical Engrs. (1927).

DISCUSSION

Mr. G. S. von Heydekampf.[1]—Mr. Peterson's paper recalls to me an experience we had some years ago at the Woehler Institute.[2] We had torsional fatigue specimens with two keyways, Fig. 1, which in the beginning consistently failed at the spot marked in the figure. The dimensions were such that even considering the stress concentration due to the keyway, the gage length was supposedly subjected to the maximum stress. The failures could not be explained by the stress concentration due to the keyway, but the action of the key itself was found to be critical.

The torque was passing through the gage length and the reinforced end of the specimen to be transmitted to the hub by means of the key. Hub and key represent relatively stiff members while the specimen is relatively flexible. The steel key No. 1 had the impossible task of deforming in accordance with the weak specimen and the stiff hub simultaneously. Apparently key No. 2 did not have to carry much load because key No. 1, through its own rigidity, took by far the greater part of the load which created extremely high local stresses combined with rubbing action. This resulted in fatigue failures.

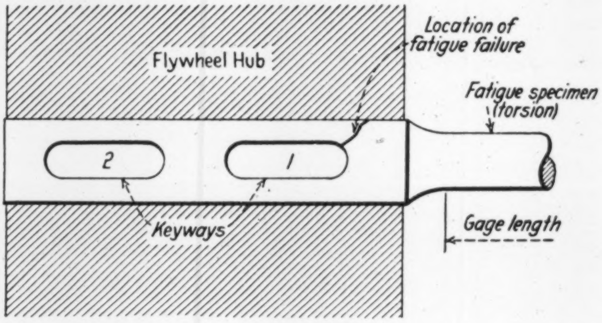

Fig. 1.—Torsional Fatigue Specimen.

The cure was obtained by making key No. 1 of copper. The lower modulus of copper would result in sufficient deformation of the key No. 1, and part of the torque could be left to key No. 2, without raising undue stress. No more failures were encountered after the copper key had been adopted.

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[1] Research Engineer, Baldwin-Southwark Corp., Southwark Division, Philadelphia, Pa.

[2] O. Foeppl and G. S. von Heydekampf, "Dauerfestigkeit und Konstruktion," *Metallwirtschaft*, p. 1087 (1929).

FATIGUE FAILURE UNDER REPEATED COMPRESSION

By H. R. Thomas[1] and J. G. Lowther[2]

Synopsis

Certain phenomena noted in connection with repeated stress tests of rails made at the University of Illinois in the course of an investigation under the auspices of the Rail Committee, American Railway Engineering Association, and of the Rail Manufacturers' Technical Committee indicated that apparently a fatigue crack could be started under cycles of repeated compressive stress involving no tensile stress.

To study these phenomena further, tests have been made on samples of structural steel. These specimens are T-shaped and are tested in bending so that the stem of the T is subjected to repetitions of compressive stress while the maximum tensile stress in the flange is distinctly lower than the compressive stress in the stem. Tests were made in a repeated-axial-stress machine fitted with an attachment for flexure tests under one-directional bending, the bending moment varying during a cycle from practically zero to a maximum, with no reversal. The machine measures load by means of an elastic ring, to which the specimen is attached.

In the tests of structural grade steel it was found that a fatigue crack will develop in the stem where the computed stress is only compressive. A discussion of the stresses involved in this type of failure is presented.

The evidence so far available indicates that for material having a well-defined yield point, when loaded as in these tests, a residual tensile stress of considerable magnitude may occur in the stem on removal of the load. That is, the stress will be partly reversed and not wholly the compressive stress that would be expected from the manner of loading.

It would seem that the effect of residual stresses may be of importance in interpreting the results in any fatigue tests where the stress varies from zero to a maximum.

Introduction

During the course of some repeated-loading tests of rail steel, in an investigation being made under the auspices of the Rail Committee, American Railway Engineering Association, and of the Rail Manufacturers' Technical Committee, it was found that cracking repeatedly occurred in a region subjected to high compressive stresses. This suggested the need for a series of tests to determine whether or not a material subjected to a repeated compressive stress shows a definite endurance limit.

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[1] Special Research Professor of Engineering Materials, University of Illinois, Urbana, Ill.

[2] Research Assistant in Mechanical Engineering, University of Illinois, Urbana, Ill.

In an attempt to obtain an answer to this question, small T-shaped specimens were tested as cantilever beams, with the stem of the beam in compression, the repeated load varying from practically zero to a maximum, with no reversal. In this T-beam, the compressive stress in the stem due to bending is about 73 per cent higher than the tensile stress in the flange. As a result of these tests, it was found that for a structural grade of steel, failure occurs by a crack starting at the extreme fiber of the stem and gradually extending toward the neutral axis. There is some evidence that after a certain point is reached, the crack may cease to grow and that complete rupture may not result.

A few tests have been made on one sample of rail steel and on one of duralumin. In the tests so far made on these materials, cracks occurred only in the portion of the beam subjected to tensile stress. While these tests are not complete, from the results so far obtained it is not expected that it will be possible in the tests yet to be made to obtain cracks in the compression area.

MATERIALS

In the limited time that this test has been in progress, results have been obtained for one soft steel of structural grade. Physical properties of this steel are:

Tensile strength, lb. per sq. in.	60 000
Yield point, lb. per sq. in.	37 000
Elongation in 2 in., per cent	31.5

The yield point in compression was the same as in tension.

TEST METHODS

In order to obtain a compressive bending stress much higher than the tensile bending stress, the test specimen was made T-shaped, with a width of flange of $\frac{3}{4}$ in., a depth of $\frac{3}{4}$ in., and thickness of flange and stem $\frac{1}{4}$ in. The moment of inertia of this section is 0.01412 in.^{4} with a section modulus for the stem of 0.0297 in.^{3}, and a section modulus for the flange of 0.0513 in.^{3} That is, with the stem in compression, the compressive unit stress is approximately 73 per cent higher than the corresponding tensile stress.

In order to apply a repeated bending stress, the T-shaped beam was clamped in a holder with one end projecting so that it was loaded as a cantilever beam with a span of 3 in. The clamping was so arranged that the specimen was gripped by the flanges, and no restraint was applied to the stem. In this way localized stress on the compression edge of the stem was avoided. Tests were made by inserting this clamp and the specimen in a repeated-axial-load testing machine which had been modified to permit its use as a one-way repeated bending machine. In this machine the specimen is loaded by means of a lever, the amount of whose movement can be adjusted by means of a variable throw cam. Load is measured by the deflection of an elastic ring, to which the end of the specimen is attached.

In making these fatigue tests it was found that there was no appreciable dropping off in load due to the formation of a crack in the stem and for that reason it was necessary to examine the specimen at frequent intervals in order to determine if cracking had occurred. This fact made the determination of an endurance limit much more of a task than with the ordinary type of fatigue specimen, where the rupture of the specimen stops the machine. Except for this, tests were made as in the usual fatigue tests.

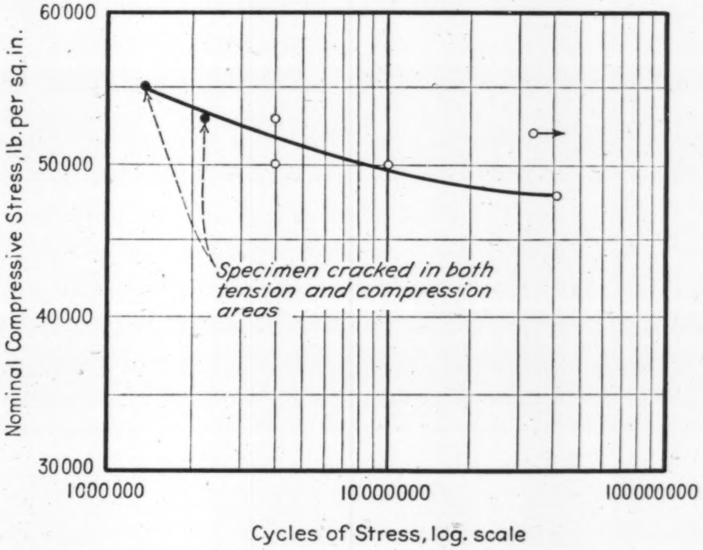

FIG. 1.—*S–N* Diagram for Sample of Structural Grade Steel.

TEST DATA AND DISCUSSION OF RESULTS

The results of these repeated stress tests are given in Fig. 1 in the form of an *S-N* diagram. It is not thought necessary to present the tabular values from which this curve was obtained.

Of the seven specimens tested, as shown in Fig. 1, two failed by both tension and compression cracks, one did not fail, and all the others failed only in the compression area. This *S-N* diagram differs markedly in one respect from the usual *S-N* diagram (reversed bending) for this grade of steel in the unusually large number of cycles required to produce failure. One specimen failed after 42,000,000 cycles; while at the highest nominal stress failure did not occur at less than 4,000,000 cycles, in those specimens failing by cracking in the stem. After one specimen had developed a crack at 42,000,000 cycles, this crack did not spread to cause complete fracture with further applications of stress up to 50,000,000 cycles. Apparently the endurance limit for compressive stress was not accurately determined at the maximum number of cycles of stress used in these tests, since it is evident that the curve has not definitely become horizontal even at 42,000,000 cycles of stress.

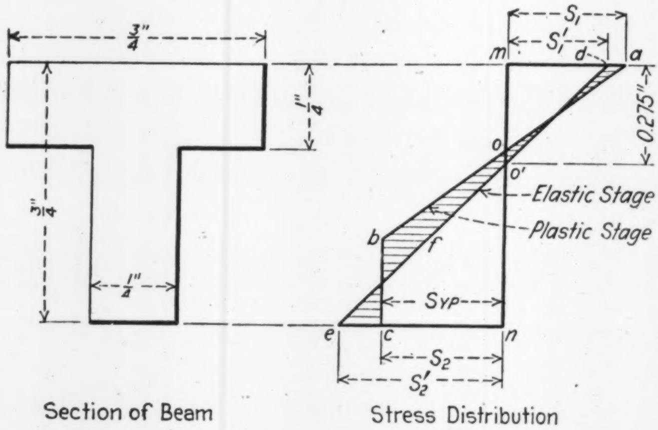

FIG. 2.—Section of T-beam and Distribution of Bending Stresses for Plastic and Elastic Bending.

Shaded area shows residual stresses on release of load causing plastic deformation.

Of particular interest in this connection is a study of the actual stress range to which the specimen was subjected, and the relation of this stress range to the nominal stress computed on the basis of elastic action. Referring to Fig. 2, line *de* represents the stress distribution on the section of the beam during the elastic stage loading of the beam. As soon as the extreme fiber stress in compression exceeds the yield point, the stress distribution will be represented with fair accuracy by line *abc,* where the distance of point *b* above *c* will depend upon the ratio of stresses *ma* to *nc.* (This is on the basis of a sharply marked yield point, as was found in the test on this material.) During this plastic yielding the neutral axis will rise, and if *ma* reaches the yield point stress the neutral axis would rise to point O, $\frac{1}{4}$ in. below the top of the flange.

After applying a load causing plastic compressive deformation, with a stress given by line *abc*, then on unloading, the specimen will act practically elastically and the unloading stress curve may be represented by line *de*. It can be shown[1] that, taking into account the varying width of the beam, the static moment of area *mdenm* about a horizontal through point O' is equal to the static moment of area *mabcnm* about a horizontal through point O, and that the shaded areas represent the residual stresses in the beam on release of load.

This method of solution indicates that the residual tensile stress *ec* is equal to the difference between the nominal compressive stress and the yield point of the material. The actual calculation of the other residual stresses on release of load is somewhat tedious, but may be facilitated by plotting curves showing the position of the neutral axis and the resisting moment (equal to the static moment of the areas), for a series of ratios of compressive stress to tensile stress for plastic stressing. These curves may then be used in solving for numerical values of the residual and other stresses. These residual stresses are wholly due to the plastic action due to bending the specimen, and are not to be confused with any initial stresses which may be present in the metal as rolled.

Using this method, and taking the yield point at 37,000 lb. per sq. in., as given for the material tested, there were obtained the following residual and elastic stresses for the nominal compressive stresses of 53,000 and 48,000 lb. per sq. in., corresponding to two of the points in Fig. 1. The notation refers to Fig. 2:

		NOMINAL COMPRESSION, 53 000 LB. PER SQ. IN.	NOMINAL COMPRESSION, 48 000 LB. PER SQ. IN.
Plastic stressing:	s_1	34 400 lb. per sq. in., tension	29 600 lb. per sq. in., tension
	s_2	37 000 lb. per sq. in., compression	37 000 lb. per sq. in., compression
Elastic stressing:	s'_1	30 700 lb. per sq. in., tension	27 800 lb. per sq. in., tension
	s'_2	53 000 lb. per sq. in., compression	48 000 lb. per sq. in., compression
Residual stresses:	$s_1-s'_1$	3 700 lb. per sq. in., tension	1 800 lb. per sq. in., tension
	$b-f$	8 700 lb. per sq. in., compression	6 600 lb. per sq. in., compression
	s'_2-s_2	16 000 lb. per sq. in., tension	11 000 lb. per sq. in., tension

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[1] S. Timoshenko, "Strength of Materials," Part I, Chapter VII, D. Van Nostrand Co., Inc., New York City (1930).

It is evident, then, that for a nominal compressive stress of 48,000 lb. per sq. in., corresponding approximately to the endurance limit of this material, when subjected to large repeated compressive stresses, failure occurs due to a stress range of which 37,000 lb. per sq. in. is the repeated compressive stress and 11,000 lb. per sq. in. is the residual tensile stress on the extreme fiber in the stem.

In this discussion of residual stresses, it is realized that the tacit assumption that all of the plastic yielding takes place on the first application of stress is not true. Undoubtedly many applications of load are required before all of the plastic deformation has occurred and the stresses then vary elastically. It is felt that this relatively slow change from the plastic to the elastic behavior does not cause any serious error in the calculations, but it would be desirable to determine what readjustment of stresses may occur during such repeated stressing. Work hardening due to stress may be an item of some consequence in a complete picture of behavior of materials stressed in this way.

As previously stated, in the tests of rail steel and duralumin, cracks developed only on the tension side of the beam. For these materials no study has yet been made of the range of stress obtained when account is taken of the residual stress due to plastic deformation. However, it is thought that the explanation of their behavior probably is to be found in the fact that these materials do not have sharply defined yield points and for that reason the residual stresses on unloading will be relatively low.

CONCLUSIONS

For materials similar to the one used, the following conclusions seem to be warranted:

1. For some kinds of steel fatigue cracks may occur in the compressive portion of a beam when subjected to repeated applications of load varying from zero to a maximum, provided the accompanying tensile stress is much less than the compressive.

2. The explanation of these cracks is to be found in the relatively high residual tensile stress on release of the load, producing a reversal of stress from a relatively low tensile stress to a comprehensive stress equal to the yield point of the material.

3. As shown by Timoshenko, the maximum residual tensile stress (*e c*, Fig. 2) is numerically equal to the difference between the nominal compressive stress on the extreme fiber and the yield point strength of the material. This statement also applies to other types of one-

way stress, other than axial stress (torsion, rectangular beams, etc.), provided the material has a sharply defined yield point.

4. In any repeated stress test of a material subjected to a one-directional stress, the residual stress on release of load (due to plastic deformation) must be taken into account in interpreting the results. This does not apply when the stresses are axial.

5. The effect of residual stresses due to plastic deformation may have an important bearing on the results obtained when fatigue tests are being made for the purpose of obtaining the effect of the range of stress on the endurance limit. This does not apply when the stresses are axial.

DISCUSSION

MR. J. B. KOMMERS[1] (*presented in written form*).—The authors are to be congratulated upon the beginning they have made in the discussion of a very interesting phase of fatigue testing.

Figure 1 of their paper indicates that the endurance limit of the beam specimen was about 47,000 lb. per sq. in. If this is true the endurance limit is 10,000 lb. per sq. in. above the original yield point, an increase of 27 per cent above the yield point.

Mehmel's tests on concrete, in which the concrete cylinders were subjected to repeated compressions, showed that there was considerable permanent deformation, but that both the elastic deformations and the permanent deformations became stable after from 200,000 to 400,000 cycles of repeated compression. This was of course for stresses below the endurance limit. The specimens of concrete adjusted themselves to the stress applied and thereafter the action was elastic action. The modulus of elasticity in the meantime had attained a lower value than its original value.

Tests on specimens having high local stresses because of abrupt changes in cross-section due to fillets or notches indicate also that materials have the power to adjust themselves to stresses which the mathematical theory of elasticity would indicate are too high to be withstood successfully. Here also there must be a local adjustment and strengthening of the material so that it finally acts elastically.

In the experiments on understressing of hot-rolled Armco iron, reported to the Society by the writer in 1930,[2] the yield point was 22,700 lb. per sq. in. and the endurance limit was 26,200 lb. per sq. in., an increase of 15.4 per cent above the yield point. By starting below the endurance limit and gradually applying small increments of stress of 500 to 600 lb. per sq. in., I have since succeeded in increasing the endurance limit about 24 per cent, which would be 43 per cent above the yield point.

I believe, therefore, that in the Illinois tests the specimen adjusts itself to the stress applied and that at the endurance limit of 47,000 lb. per sq. in. the residual tensile stress on the compressive fiber has disappeared and that the cycle of stress is from zero to 47,000 lb. per sq. in. in compression, the specimen acting elastically.

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[1] Professor of Mechanics, Engineering College, University of Wisconsin, Madison, Wis.

[2] J. B. Kommers, "The Effect of Under-Stressing on Cast Iron and Open-Hearth Iron," *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part II, p. 368 (1930).

One of the matters which is of interest in this connection is whether the modulus of elasticity of the material has been decreased by the repeated stresses, as is the case for concrete, or whether it remains constant, as one would naturally expect for steel. If it were possible to measure deformations this question could be answered.

MESSRS. H. R. THOMAS[1] AND J. G. LOWTHER[2] (*authors' closure by letter*).—Mr. Kommers' comments are very interesting but we find ourselves unable to agree with his conclusion that when the specimen is stressed at the endurance limit the residual tensile stress on the compressive fiber disappears and the stress cycle then varies from zero to a maximum. Mr. Kommers' conclusion is based on tests in which the applied stress is either completely reversed or is axial, but neither of these is the stress condition for the T-beams. This residual tensile stress is due to the elastic stress in other portions of the section, and so long as the tensile stress in the flange is below the yield point it is difficult to see how any readjustment can cause the residual tensile stress to become zero.

A series of tests to determine the effect of understressing on the endurance limit of a material subjected to a one-way bending stress, using a T-shaped section, might throw some further light on the way in which understressing increases the endurance limit.

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EFFECT OF ZINC COATINGS ON THE ENDURANCE PROPERTIES OF STEEL

By W. H. Swanger[1] and R. D. France[2]

Synopsis

The effect of the surface alterations, resulting from the application and presence of hot-dipped galvanized and electroplated zinc coatings, on the endurance properties of open-hearth iron and 0.45-per-cent and 0.72-per-cent carbon steel was determined by fatigue tests made with R. R. Moore rotating beam and Haigh axial loading machines.

Rotating-beam tests were made on: (1) polished but uncoated specimens; (2) specimens coated by the hot-dip galvanizing process; (3) zinc-plated specimens; and (4) on specimens acid pickled as for galvanizing. Axial loading tests were made on uncoated and galvanized specimens only.

The open-hearth iron was tested in the "as-rolled" condition. The two carbon steels were tested in the normalized and annealed condition, in the quenched condition, and in the tempered condition, except that axial loading tests were not made on quenched specimens.

The results of the fatigue tests are given in conventional *S-N* diagrams and are summarized in a table together with the results of tensile strength and hardness determinations. Micrographs showing the structures of the heat-treated steels and of the two types of coatings are given.

The endurance ratios (endurance limit to tensile strength) by the rotating-beam method of test of the uncoated specimens varied from 0.38 to 0.70; by the axial loading method, from 0.31 to 0.59.

The decrease in endurance limit from that of the polished, uncoated materials caused by the acid pickling was more marked in the quenched steels than in the annealed and the tempered steels. The decrease varied from 0 to 40 per cent.

A still greater decrease, as much as 42.5 per cent, was caused by the presence of the hot-dipped galvanized coatings. The quenched and the tempered steels were affected more adversely than the annealed steels.

The endurance limits of the zinc electroplated specimens were equal to or greater than those of the uncoated specimens.

The difference in the effects of the two types of coating is believed to be caused by the differences in the nature of the bond between zinc and the steel, and the structure and hardness of the two coatings.

Introduction

It is generally agreed that the character of the surface of a metal is an important factor in determining its resistance to repeated stresses. If an endurance limit is accepted as an intrinsic property of a metal, this limit is correctly determined only when smoothly polished specimens with generous fillets are used. The damaging effects of surface corrosion and of mechanically produced notches have formed the subject of numerous investigations on "fatigue of metals." The information gained from these investigations has shown the necessity for avoiding "notch-effects" in highly stressed members subjected to repeated stresses. Careful removal of tool marks, protection from corrosion, and use of adequate fillets at abrupt changes of section aid materially in realizing in practice the normal endurance strength of metals.

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[2] Assistant Metallurgist, U. S. Bureau of Standards, Washington, D. C.

Metallic coatings are frequently used on iron and steel to protect against corrosion. It is a matter of considerable interest to know what effect such metallic coatings may have upon the endurance limit of metals when damage by corrosion is not involved. From a mechanical standpoint the presence of a metallic coating on a specimen of iron or steel introduces factors which complicate this problem. There are two surfaces, the free surface of the coating and that of the underlying steel, the characteristics of which may influence the endurance limit of the composite specimen. Another factor is the endurance strength of the coating itself. Very little is known about this property of the various protective metallic coatings in general use, but it is probably low in comparison with the endurance strength of steels. The nature of the bond or interface between coating and steel is believed to have a very important influence on the endurance properties of the composite specimen. The nature of the surface of the steel, the kind of coating and the manner in which it is applied largely determine the character of the bond between coating and steel.

TABLE I.—HEAT TREATMENT OF CARBON STEELS.

	Normalizing[a]		Annealing[b]		Quenching[c]		Tempering[d]	
	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.
0.45-per-cent carbon steel annealed	1607	875	1472	800	....	...	....	...
Quenched	1607	875	1472	800	1526	830	....	...
Tempered	1607	875	1472	800	1526	830	1103	595
0.72-per-cent carbon steel annealed	1463	795	1409	765	....	...	....	...
Quenched	1463	795	1409	765	1427	775	....	...
Tempered	1463	795	1409	765	1427	775	842	450

[a] $\frac{3}{4}$-in. rods, heated with furnace, held 20 minutes, air cooled.

[b] $\frac{3}{4}$-in. rods, heated with furnace, held 40 minutes, cooled with furnace.

[c] Machined test bars, heated with furnace, held 20 minutes, quenched in oil.

[d] Machined test bars, heated with furnace, held 60 minutes, cooled with furnace.

This investigation was restricted to a study of the effect of hot-dipped galvanized and electroplated zinc coatings on the endurance properties of low-carbon open-hearth iron and two carbon steels.

MATERIALS

Zinc coatings were chosen because they are the most commonly used protective metallic coatings on ordinary structural grades of iron and steel. Both hot-dipped galvanized and electroplated coatings were used because of the known difference in the nature of the bond between steel and zinc coating of these two types. Sherardized, "galvannealed" and sprayed zinc coatings were not studied. It is believed that the difference in the nature of the bond of hot-dipped galvanized coatings and sherardized or "galvannealed" coatings, and of electrodeposited coatings and sprayed zinc coatings, is one of degree rather than of kind. It is of course possible that each of the above mentioned types of zinc coatings might affect the endurance properties of a given steel to a different degree.

The open-hearth iron and the two carbon steels were purchased from jobbers and were not specially made for this investigation. The chemical compositions of the three materials (ladle analyses) are given below:

	CARBON, PER CENT	MANGANESE, PER CENT	PHOSPHORUS, PER CENT	SULFUR, PER CENT	SILICON, PER CENT
Open-hearth iron...........	0.02	0.03	0.042	0.005	....
0.45-per-cent carbon steel...	0.45	0.60	0.015	0.040	0.18
0.72-per-cent carbon steel...	0.72	0.31	0.017	0.019	0.24

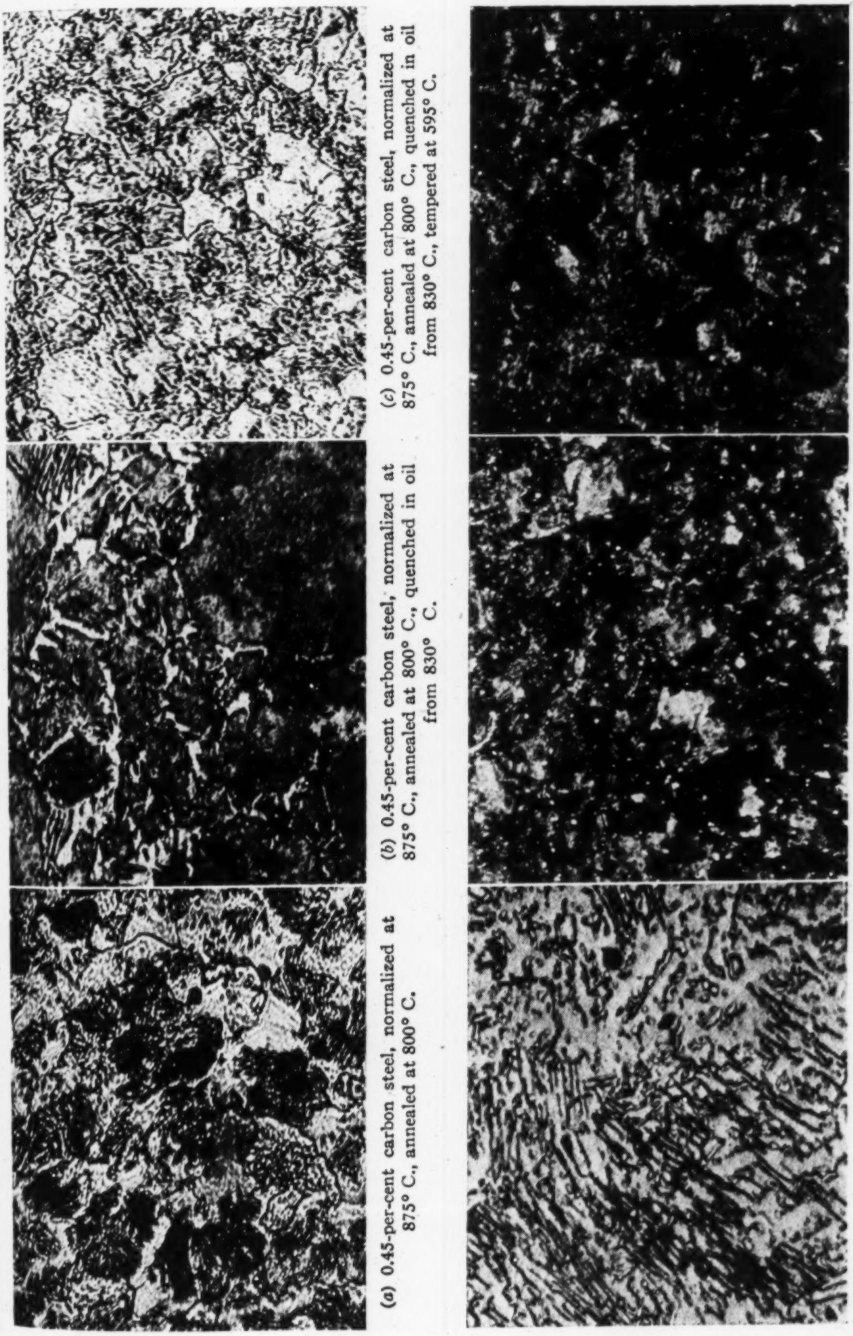
The open-hearth iron test specimens were machined from the center of 1-in. diameter hot-rolled bars and the specimens of the two carbon steels from the center of corresponding bars of $\frac{3}{4}$-in. diameter.

All of the specimens were carefully machined on a lathe and finish ground to size. They were then polished longitudinally until all traces of circumferential tool marks were eliminated with emery papers of successively finer grit, ending with 0000 paper.

Endurance limits of the two carbon steels, coated and uncoated, were determined with the steels in the normalized and annealed condition, in the oil-quenched condition, and in the tempered condition. The details of the heat treatments are given in Table I.

To minimize any decarburization effect, an atmosphere of illuminating gas was maintained in the furnace during the heat treatments. As a further precaution, the hardened specimens were machined oversize and a layer 0.005 in. thick was ground off the test length after the heat treatments.

The open-hearth iron was used in the "as-rolled" condition.



(a) 0.45-per-cent carbon steel, normalized at 875° C., annealed at 800° C.

(b) 0.45-per-cent carbon steel, normalized at 875° C., annealed at 800° C., quenched in oil from 830° C.

(c) 0.45-per-cent carbon steel, normalized at 875° C., annealed at 800° C., quenched in oil from 830° C., tempered at 595° C.

(d) 0.72-per-cent carbon steel, normalized at 795° C., annealed at 765° C.

(e) 0.72-per-cent carbon steel, normalized at 795° C., annealed at 765° C., quenched in oil from 775° C.

(f) 0.72-per-cent carbon steel, normalized at 795° C., annealed at 765° C., quenched in oil from 775° C., tempered at 450° C.

FIG. 1.—Structure of the Carbon Steels, Etched with Nital (alcohol containing 2 per cent of nitric acid) (× 500).

The microstructures of the two carbon steels in the three conditions of heat treatment are shown in Fig. 1.

The galvanized coatings were applied by the Research Division of the New Jersey Zinc Co. by a method approximating commercial practice for hot-dip galvanizing. The specimens to be galvanized were first polished to the same degree as the specimens tested in the uncoated condition. They were then dipped in a hydrochloric acid solution (2 parts water to 1 part hydrochloric acid, sp. gr. 1.19) for two minutes and immediately into the zinc bath held at 440° C. (824° F.). A high-grade zinc (containing 99.94+ per cent zinc) was used. The weight of coating obtained varied from 1.6 to 2.0 oz. per sq. ft. The galvanized coatings actually obtained varied from 0.0017 to 0.0035 in. in thickness. This variation in thickness was probably caused by the fact that some of the specimens had to be dipped more than once to obtain a complete coating. The length of time in the zinc bath accordingly varied from 45 to 100 seconds.

In order to distinguish between the effect of the acid pickling and the combined effect of pickling and galvanizing, fatigue tests were made on specimens of each material which, after final polishing, had been dipped for two minutes into hydrochloric acid of the same strength used for the galvanized specimens.

The specimens of the quenched 0.45 and 0.72-per-cent carbon steels which were not galvanized were dipped into a lead bath for 45 seconds at 440° C. (824° F.) so that they had the same heat treatment as the corresponding hot-dipped galvanized specimens. A final polish with 0000 emery paper was given to the lead-dipped specimens before they were dipped into the acid or tested.

The electroplated zinc coatings were applied at the U. S. Bureau of Standards.[1] The procedure was as follows:

1. Cathode-electrolytic cleaning—2 minutes, at 90° C.,
2. Hot water rinse,
3. Cold water rinse,
4. Pickled in sulfuric acid (2 *N*)—2 minutes at 50° C.,
5. Hot water rinse,
6. Hot alkali dip without current—2 minutes,
7. Scrubed with cleaning solution—bristle brush,
8. Plated in acid zinc bath, 24 minutes 1.5 ampere—35° C.

The electrolytic cleaner was made up as follows:

Sodium carbonate—30 g. per liter.
Trisodium phosphate—30 g. per liter.
Sodium hydroxide—7.5 g. per liter.

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[1] The plating was done by the Electrochemistry Laboratory under the supervision of W. Blum.

The zinc anodes for the electroplating process were of the same order of purity as the zinc used for the hot-dipped coatings. The thickness of the electrodeposited coatings varied from 0.0021 to 0.0031 in., which is roughly equivalent to a 2-oz. coating.

TESTING PROCEDURE

The endurance limit determinations were made by both the rotating-beam and the axial-loading methods of stressing. The rotating-beam tests were made on R. R. Moore machines and the axial-loading tests were made on Haigh alternating stress testing machines, in which the specimens were subjected to alternating equal tensile and compressive stresses. The form of the specimens, methods of calibration of the testing machines, and testing procedure followed have been described previously by one of the authors(1).[1]

TABLE II.—PHYSICAL PROPERTIES AND RESULTS OF ENDURANCE TESTS.

Materia	Heat Treatment	Tensile Strength, lb. per sq. in.	Brinell Hardness Number	Rockwell Hardness Number	Rotating-Beam Method							
					Uncoated		Pickled		Galvanized		Electroplated	
					Endurance[a] Ratio	Endurance Limit, lb. per sq. in.	Endurance Limit, lb. per sq. in.	Change in Endurance Limit, per cent	Endurance Limit, lb. per sq. in.	Change in Endurance Limit, per cent	Endurance Limit, lb. per sq. in.	Change in Endurance Limit, per cent
0.02-per-cent carbon..	Hot rolled	44 000	90	51 B	0.61	27 000	22 000	−18.5	26 000	− 4.0	27 500	+ 1.8
0.45-per-cent carbon..	Annealed	81 000	153	84 B	0.44	36 000	33 000	− 8.0	27 000	−25.0	......	......
0.45-per-cent carbon..	Quenched	121 500	248	28 C	0.65	80 000	60 000	−25.0	46 000	−42.5	......	......
0.45-per-cent carbon..	Tempered	102 000	207	98 B	0.45	46 500	46 500	......	40 000	−14.0	49 000	+ 5.5
0.72-per-cent carbon..	Annealed	92 000	192	93 B	0.38	35 000	31 500	−10.0	30 500	−13.0	35 000	......
0.72-per-cent carbon..	Quenched	176 000	340	39 C	0.70	124 500	75 000	−40.0	75 500	−40.0	......	......
0 72-per-cent carbon..	Tempered	168 500	332	37 C	0.56	94 000	87 000	− 7.5	54 500	−42.0	105 000	+11.0
					Axial-Loading Method[b]							
0.02-per-cent carbon..	....	....	....	....	0.59	26 000	......	......	22 500	−13.5	......	......
0.45-per-cent carbon..	....	....	....	....	0.31	25 500	......	......	24 500	− 4	......	......
0.45-per-cent carbon..	....	....	....	....	....	......	......	......	......	......	......	......
0.45-per-cent carbon..	....	....	....	....	0.45	46 000	......	......	30 000	−35	......	......
0.72-per-cent carbon..	....	....	....	....	0.31	29 000	......	......	28 500	− 2	......	......
0.72-per-cent carbon..	....	....	....	....	....	......	......	......	......	......	......	......
0.72-per-cent carbon..	....	....	....	....	0.37	62 500	......	......	47 000	−25	......	......

[a] Endurance ratio = $\frac{\text{endurance limit}}{\text{tensile strength}}$.

[b] Physical properties are the same as shown above.

Axial loading tests were not made on zinc-plated specimens as it was believed that the effect of the electrodeposited coating on the endurance limit determined by this method would be of the same order as was found for the rotating-beam tests. As a further economy in number of specimens, axial loading tests were not made on the

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[1] The boldface numbers in parentheses refer to the papers given in the list of references appended to this paper, see p. **448**.

0.45 and 0.72-per-cent carbon steels in the quenched condition because these steels are seldom used in this condition. Rotating-beam tests of electroplated specimens of the 0.72-per-cent carbon steels in the quenched condition and of the 0.45-per-cent carbon steel in the annealed and in the quenched conditions were also omitted.

Usually nine specimens were used in the determination of each endurance limit. One specimen of each series, except the pickled specimens, tested on the Moore machines was subjected to 25 million cycles of reversed stress at the endurance limit and then re-stressed at a value 5000 lb. per sq. in. above the endurance limit. An annealed, a quenched, and a tempered specimen of the 0.45-per-cent carbon steel and an annealed and a tempered specimen of the 0.72-per-cent carbon steel were stripped of their galvanized coatings after which they were tested at a stress just under the endurance limit determined on the acid-pickled specimens of the corresponding materials.

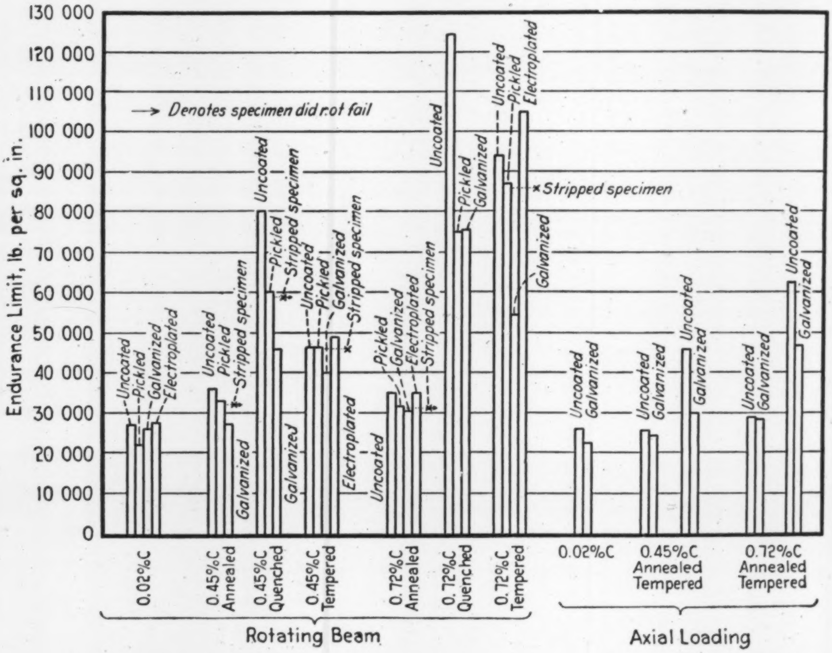

FIG. 2.—Fatigue Limits Determined by Rotating-Beam and Axial-Loading Methods for Open-Hearth Iron, 0.45 and 0.72-per-cent Carbon Steels, in the Annealed, Quenched, and Tempered Conditions.

The stresses applied to the acid-pickled and the coated specimens were calculated on the diameter of the polished specimen before it was pickled or coated. The diameters were measured with a special micrometer capable of a precision of ± 0.0001 in. The change in diameter caused by either the acid treatment alone or the acid treatment and the application of the zinc coating was in all cases less than 0.0002 in.

The tensile strengths of the three materials were determined on standard 0.505-in. diameter test specimens, heat treated in the same way as the endurance specimens. Hardness determinations were made on the ends of the tension and endurance test specimens.

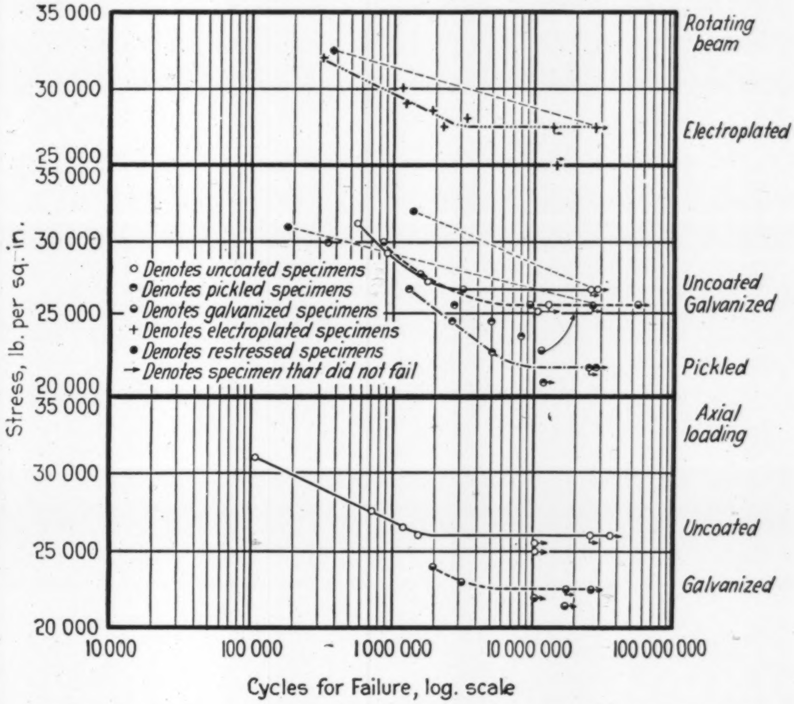

FIG. 3.—*S-N* Diagrams for Fatigue Tests of 0.02-per-cent Carbon Open Hearth Iron.

RESULTS

The results of the endurance limit determinations are given in Table II together with the tensile strengths and hardness of the steels and the percentage change in endurance limits caused by the pickling, by the pickling and galvanizing, and by the electroplating. The endurance limits are also shown graphically in Fig. 2.

Conventional *S-N* diagrams for all of the fatigue limit determinations are given in Figs. 3 to 9.

DISCUSSION

The endurance limits of the specimens that had been dipped in acid were lower than the endurance limits of the polished uncoated specimens of the corresponding materials. The decrease was not uniform for the different materials but ranged from zero for the tempered 0.45-per-cent carbon steel to 40 per cent for the quenched 0.72-per-cent carbon steel. This result was clearly a manifestation of the "notch-effect" caused by the acid treatment and was of the same nature as the corrosion effect which has been shown by McAdam(2,3) to have a pronounced influence on the endurance properties of metals.

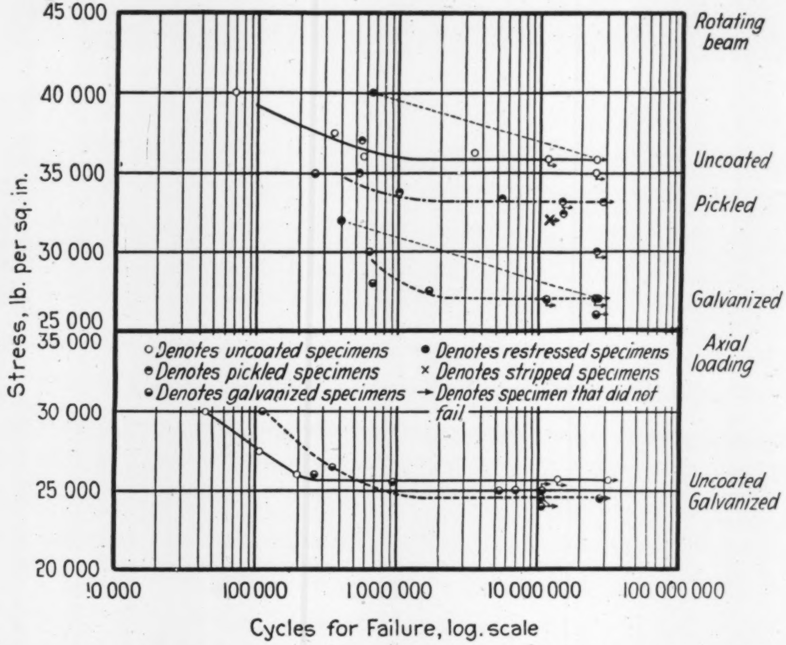

FIG. 4.—*S-N* Diagrams for Fatigue Tests of 0.45-per-cent Carbon Steel, Annealed.

The variations in the effect of the acid treatment on the endurance limits are undoubtedly associated with different solubility rates of the materials in the three conditions of heat treatment. The difference in the surface contours of the steel in different specimens of any one series was of about the same magnitude as the difference between the three series of specimens (acid pickled, galvanized, and electroplated). Figure 10 shows, in longitudinal section, typical surface contours of the steel of the specimens after the various treatments.

The decrease in endurance limit resulting from the acid treatment was much greater for the quenched carbon steels than for the annealed or tempered steels. This is in accord with the generally accepted idea that a hard steel with low ductility is more susceptible to notch effects than a softer and more ductile steel.

There was a marked decrease in the endurance limit of the galvanized materials as determined by the rotating-beam method except for the open-hearth iron, for which there was little if any difference (4.0 per cent). For the carbon steels the decrease ranged from 13 to 42.5 per cent. By the axial loading method of test the decrease for the open-hearth iron was 13.5 per cent and for the carbon steels the decrease was much greater in the tempered steels than in the annealed steels.

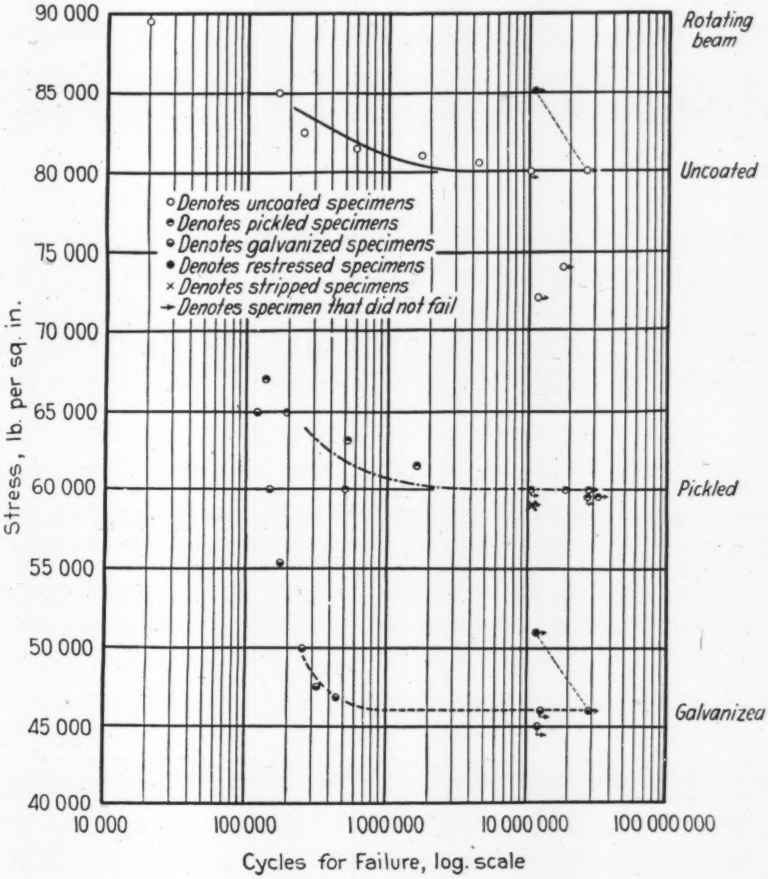

FIG. 5.—*S-N* Diagrams for Fatigue Tests on 0.45-per-cent Carbon Steel, Quenched.

Except for the open-hearth iron and the quenched 0.72-per-cent carbon steel, the decrease in endurance limit was greater for the galvanized than for the acid-pickled material. It might be considered that this further decrease was caused by an increased pitting or notch effect on the surface of the steel by the action of the zinc in the galvanizing process. That the pitting due to galvanizing was not the only cause of the decreased endurance limits of the galvanized specimens is indicated by the fact that specimens of the annealed and the quenched 0.45-per-cent carbon steels, and of the annealed 0.72-per-cent carbon steels that had been galvanized, did not fail in 10 million cycles in the rotating-beam machines at stresses just under the endurance limits of the acid-pickled materials, when the

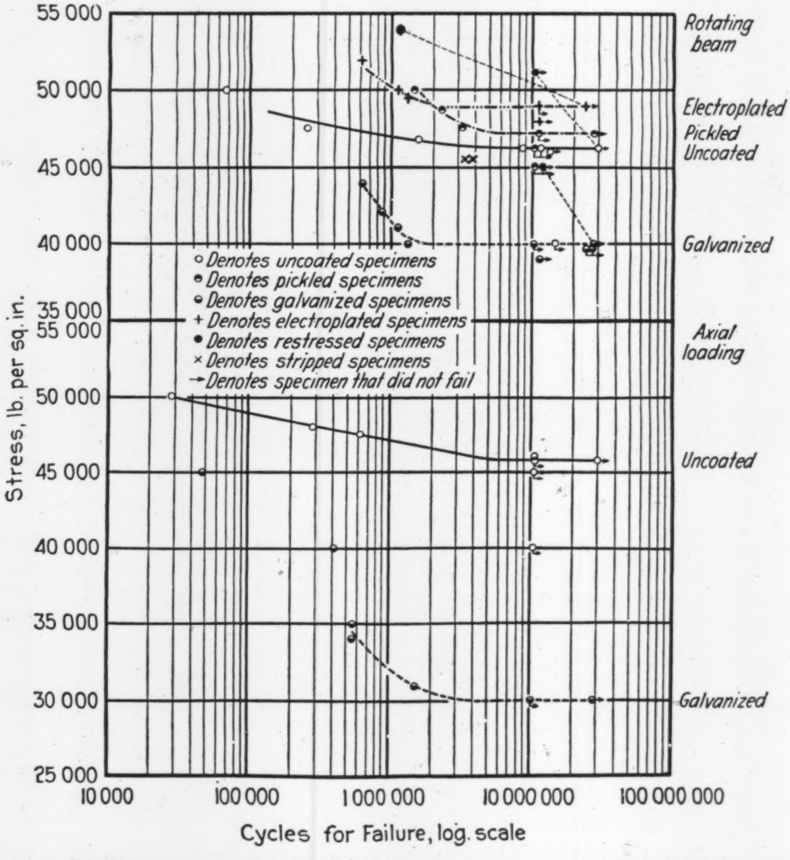

FIG. 6.—*S-N* Diagrams for Fatigue Tests on 0.45-per-cent Carbon Steel, Tempered.

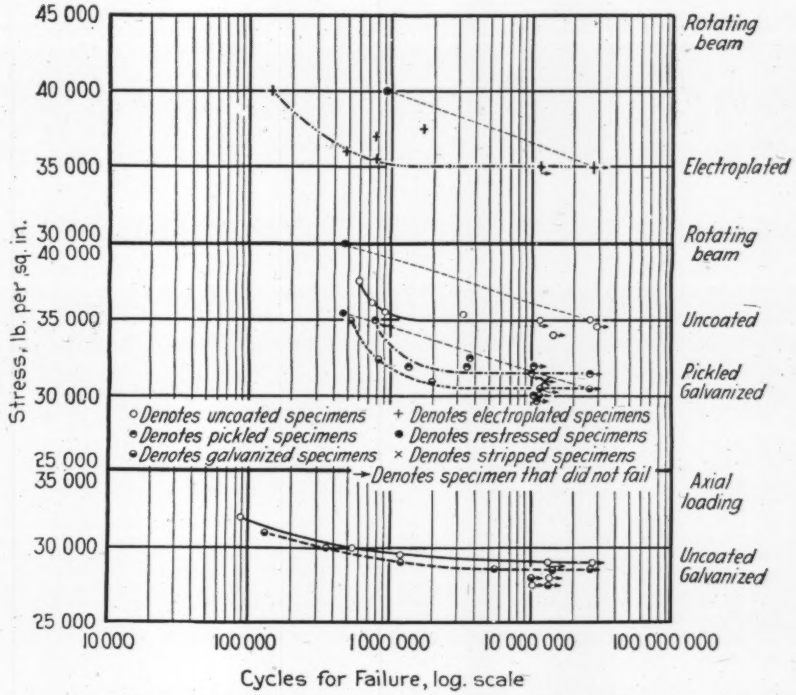

FIG. 7.—*S-N* Diagrams for Fatigue Tests on 0.72-per-cent Carbon Steels, Annealed.

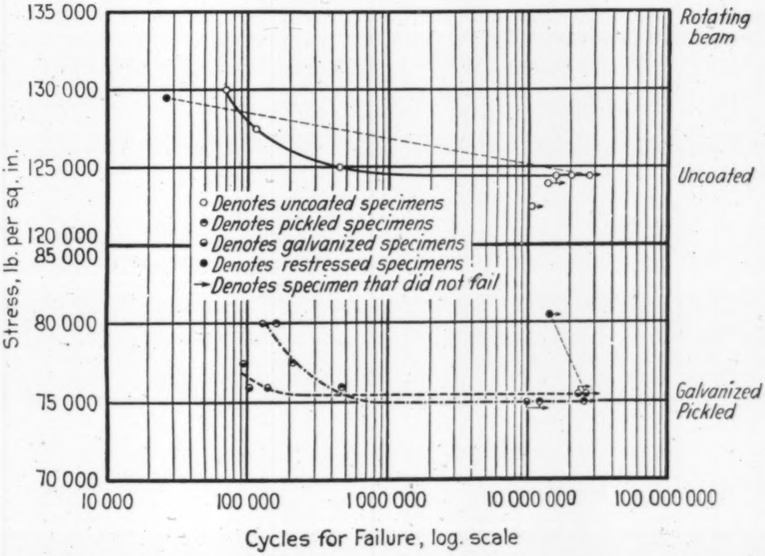

FIG. 8.—*S-N* Diagrams for Fatigue Tests on 0.72-per-cent Carbon Steel, Quenched.

galvanized coatings were stripped off with acid.[1] The stripped specimen of the tempered 0.45-per-cent carbon steel failed after 3,500,000 cycles which indicated that its endurance limit was not much lower than the stress at which it failed. The stripped specimen of the tempered 0.72-per-cent carbon steel failed after 300,000 cycles but at a stress 32,000 lb. per sq. in. higher than the endurance limit of the galvanized material.

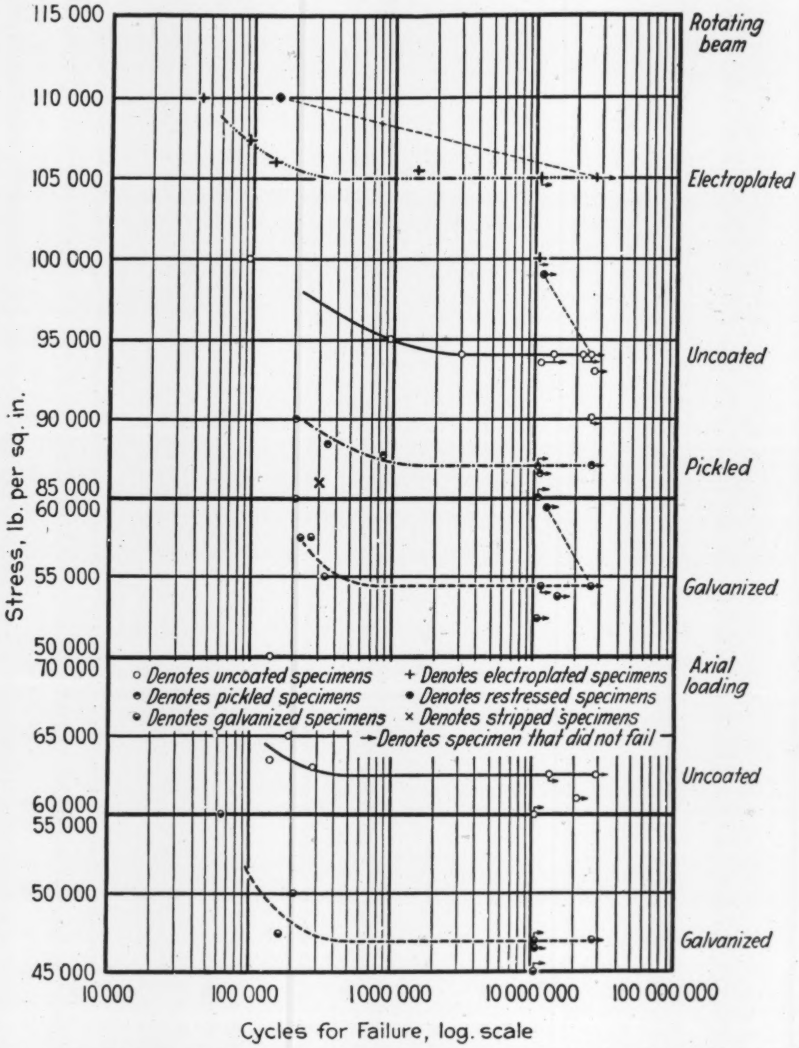

FIG. 9.—*S-N* Diagrams for Fatigue Tests on 0.72-per-cent Carbon Steel, Tempered.

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[1] The zinc coatings were dissolved in hydrochloric acid (sp. gr. 1.19) containing 1 ml. of antimony chloride solution (32 g. of $SbCl_3$ in 1000 ml. HCl (sp. gr. 1.19)) to 100 ml. of acid (A.S.T.M. Methods A 90 – 30).

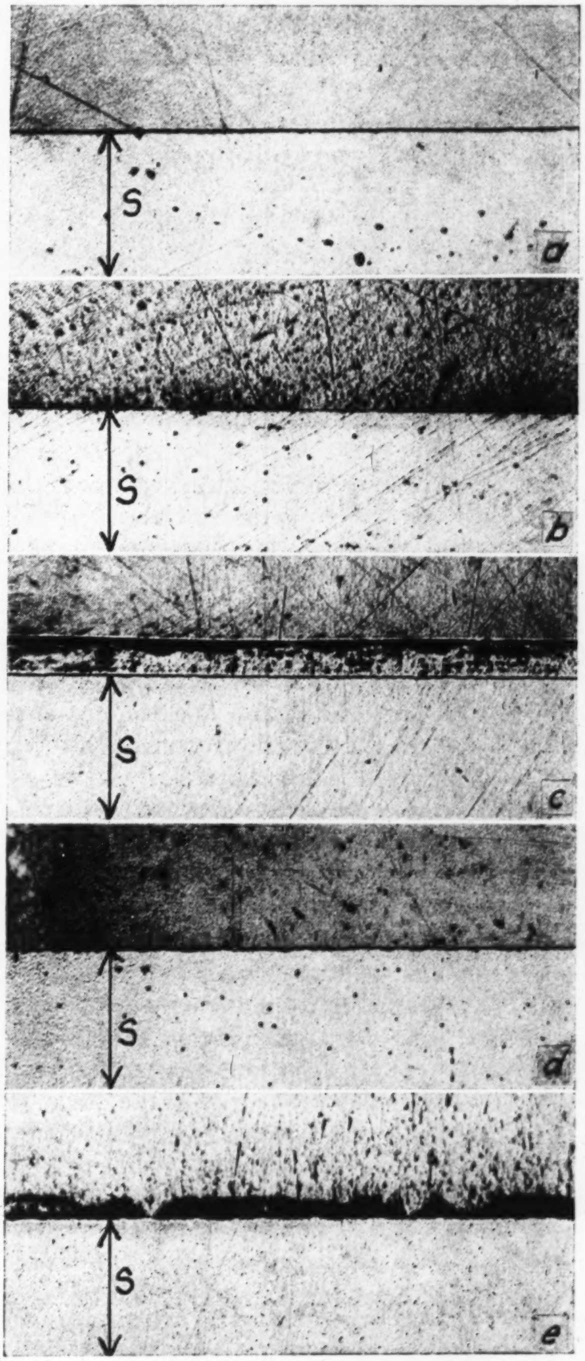


FIG. 10.—Typical Contours of the Steel Surface of Specimens, Unetched (× 50).

(*a*) Polished.
(*b*) Polished and then acid pickled.
(*c*) Polished, acid pickled and then galvanized.
(*d*) Polished, acid pickled, galvanized and then stripped.
(*e*) Polished and then electroplated.

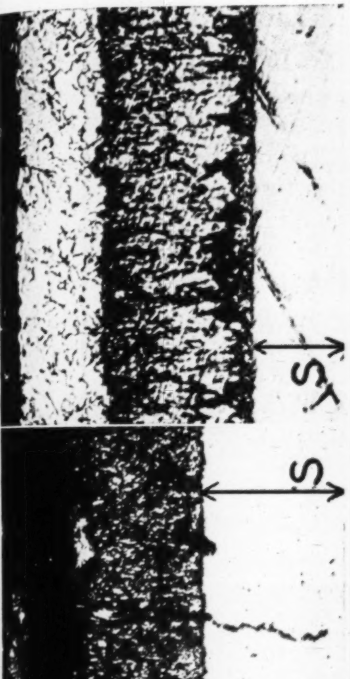
Hence it is believed that the conclusion is warranted that the presence of a hot-dip galvanized coating causes a serious lowering of the endurance limit of carbon steels below that which would be obtained in the same steels in the polished but uncoated condition.

A similar conclusion can be drawn from the results of investigations by Harvey(4,5), Haigh(6), and Fuller(7) of the protection against corrosion-fatigue afforded to steels by galvanized or other types of metallic coatings. Although their results showed that the endurance properties of the coated metals were definitely better than for the uncoated metals, when subjected to simultaneous stress and corrosion, the corrosion-fatigue limits of the galvanized materials were at the same time lower than the endurance limits of the uncoated materials not subjected to corrosion.

In marked contrast to the lower endurance limit of the galvanized specimens, the endurance limits of the zinc-plated specimens of the softer steels were equal to those of the corresponding uncoated specimens. The endurance limits of the zinc-plated specimens of the tempered steels were higher than those of the corresponding uncoated specimens by 5.5 per cent for the medium carbon and 11 per cent for the higher carbon steel.

Both the hot-dip galvanized and the electroplated specimens had been subjected to comparable acid treatments before the coatings were applied. Furthermore the steels of each series were identical in composition and had received the same heat treatments. Hence any differences in endurance properties of the galvanized and electroplated specimens of the same series cannot be ascribed to differences in the steels themselves, particularly to any suspected differences in rate of notch propagation. It is believed that the increased endurance limits of the electroplated coatings were not the result of a strengthening effect of the zinc coating itself. Numerous cracks were found in both types of coatings in the more highly stressed portions of the specimens after they were removed from the testing machines. This indicates that the maximum fiber stresses in the coatings were above their endurance limits. It is reasonable to expect that the endurance strength of the glavanized coating was higher than that of the electrodeposited zinc. Consequently any strengthening effect from the coating would be expected to be derived more from the galvanized than from the electrodeposited coating.

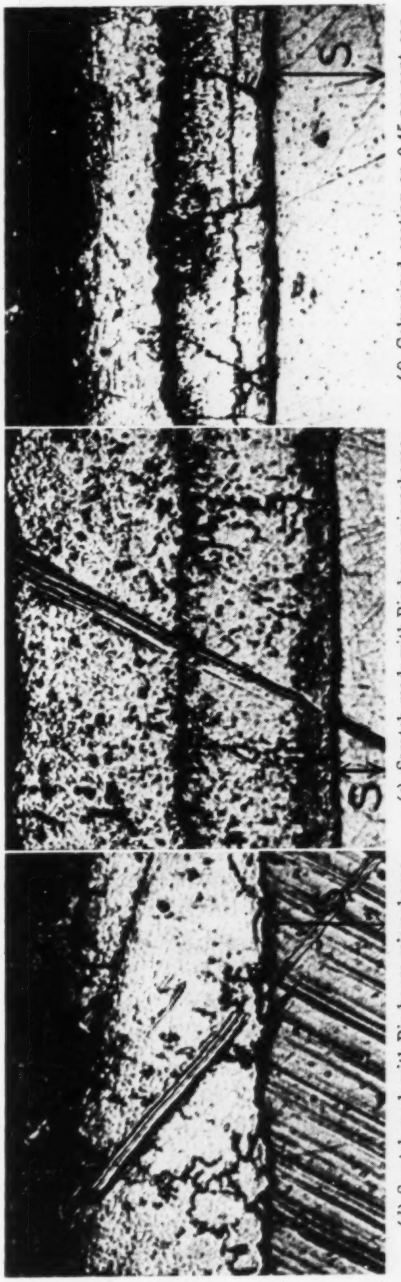
The two types of coating are different in many respects. The electrodeposited coatings, as would be expected, were homogeneous throughout. The bond between zinc and steel may have been a "molecular bond," but at the interface there was little if any diffusion



(*a*) Structure of electrodeposited zinc coating on 0.72-per-cent carbon steel, annealed.

(*b*) Crack in galvanized coating extending into steel, 0.45-per-cent carbon, annealed.

(*c*) Structure of galvanized coating on 0.45-per-cent carbon steel, annealed. Note the relatively thick intermediate layer, thin innermost layer, and light colored outer layer of relatively pure zinc.



(*d*) Scratch made with Bierbaum microcharacter across electrodeposited zinc coating on tempered 0.72-per-cent carbon steel. Discontinuity of scratch between zinc and steel was caused by difference in elevation between zinc and steel.

(*e*) Scratch made with Bierbaum microcharacter across galvanized coating on tempered 0.45-per-cent carbon steel. Note differences in width of scratch in outer zinc layer and intermediate and innermost iron-zinc alloy layers. Note that innermost alloy layer appears to be harder than the steel.

(*f*) Galvanized coating on 0.45-per-cent carbon steel tempered. Note the thickness of the inner, hard, brittle layer adjacent to the hardened steel as compared with the thin layer of similar composition next to the softer steel of photomicrograph (*c*).

FIG. 11.—Photomicrographs Showing Structures of Zinc Coated Specimens. Etched with chromic acid solution containing sodium sulfate (20 g. CrO_3, 1.5 g. Na_2SO_4 in 100 cc. H_2O) (× 300). Arrows denote extent of steel.

of iron into the zinc. Figure 11(*a*) shows a typical cross-section of the electroplated steel specimen.

The structure of hot-dipped galvanized coatings on steel has been studied by a number of investigators(8,9,10). Without going into a detailed discussion of the composition of the layers it suffices at this time to state that the galvanized coatings on the specimens used in this investigation consisted of at least three layers. The outer layer was predominately pure zinc, the innermost layer consisted largely of the more or less well known iron-zinc intermetallic compounds. The intermediate layer consisted largely of intermetallic compound or compounds interspersed in a zinc matrix. On the annealed steel and the open-earth iron specimens, the intermediate layer was relatively much thicker than the innermost layer, whereas on the quenched and on the tempered steels, the thickness of the innermost layer approached that of the intermediate layer.

Figure 11(*c*) and (*f*) show in cross-section the galvanized coatings on an annealed and on a quenched 0.45-per-cent carbon steel. The difference in thickness of the inner, iron-rich layers is marked. Possibly a difference in solubility in zinc of the heat-treated steel and the annealed steel or open-hearth iron is responsible for the difference in thickness of the alloy layers.

The scratch hardness of the two types of coating indicated that the outer layer of the galvanized coatings was of the same order of hardness as the electrodeposited coatings. The intermediate and inner layers of the galvanized coatings were increasingly harder as the steel surface was approached. This is illustrated in Fig. 11 (*d*) and (*e*). The alloy layer adjacent to the steel, Fig. 11 (*e*) appears to be even harder than the steel itself.

As stated before, there were numerous cracks in both types of coating of the tested specimens. In the electrodeposited coatings the cracks were irregular, Fig. 11(*a*), and appeared to be intergranular. In the galvanized coatings there were many more cracks in the intermediate and innermost layers than in the outer layer. Many of the cracks appeared to have started in the layer adjacent to the steel and to have progressed toward the outer surface, and in some instances the surface was not quite reached. In many instances the cracks undoubtedly originated at the surface and progressed inwardly toward the steel.

Of the broken specimens which were sectioned for examination under the microscope, two were found in which there was a crack in the steel which was a continuation of a crack in the inner layer of the galvanized coating. One of these is shown in Fig. 11(*b*). Although there were many cracks in the galvanized coatings, the evidence indicated that only a few had advanced into the steel. The probability is that none of the cracks in the electrodeposited coatings had extended into the steel, and that the cracks which caused failure of the electroplated specimens in the fatigue test originated in the steel itself.

The explanation of the lower endurance limits of the galvanized specimens as compared with the uncoated or electroplated specimens is believed to lie: (1) in the difference in the stress conditions at the bottom of a crack in the inner, relatively hard layers of the galvanized coating and those in a similar crack in the softer electrodeposited zinc; and (2) in the difference in the nature of the bond between zinc and steel in the two types of coating.

It has been shown (11) that in relatively soft and ductile metals subjected to repeated stresses, slip lines form either previously to, or subsequently to, the appearance of cracks and that the cracks advance in the direction of the slip lines. The slip lines are an indication of plastic deformation under an applied stress which decreases when the deformation occurs. It is believed that the zinc of the electrodeposited coatings had sufficient ductility to deform around the bottom of an advancing crack, and that the resulting decrease in stress concentration when the crack had advanced to the steel was sufficient to stop the crack at that point. The discontinuity between zinc and steel was an additional aid in halting further advance of the crack. Consequently the normal endurance limit of the steel was attained.

In the case of the galvanized specimens, a crack advancing into the relatively hard and very brittle inner layers did not meet with any conditions conducive to a decrease of stress concentration. The crack progressed to the outer steel fibers with undiminished stress. The intimate bond between coating and steel offered no obstacle to the advance of the crack into the steel. Naturally not every crack produced in the coating in the course of the fatigue test penetrated into the steel. A fortuitous combination of maximum stress concentration and conditions at the surface of the steel most favorable to the propagation of the stress, determined the location of the crack which led to failure of the specimen. Consequently since the presence of a hot-dipped galvanized coating promotes stress concentrations, the endurance limit of such a coated specimen was appreciably lower than the normal endurance limit of the steels.

The data obtained on the specimens which were re-stressed at 5000 lb. per sq. in. above the endurance limit, after they had been subjected to 25 million cycles of stress at the endurance limit, indicated that only the quenched and the tempered steels were appreciably strengthened by the previous understressing. All of the annealed carbon steel and open-hearth iron specimens tested failed to "run" at the higher stress. The 0.72-per-cent carbon steel specimen, uncoated, and the two electroplated specimens of the 0.72 and the 0.45-per-cent carbon steel, in the tempered condition, also failed to run.

The interesting observation was made that distinct spangles were developed on the surface of the zinc of the galvanized specimens shortly after they were placed in operation in the rotating-beam machines.

Acknowledgment:

Grateful acknowledgment is made by the authors to P. R. Kosting of the staff of the Division of Metallurgy of the U. S. Bureau of Standards for his aid in the preparation of the micrographs of the zinc coatings and in the scratch hardness tests.

REFERENCES

(1) R. D. France, "Endurance Testing of Steel: Comparison of Results Obtained with Rotating-Beam *versus* Axially-Loaded Specimens," *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part II, p. 176 (1931).

(2) D. J. McAdam, Jr., "Influence of Water Composition on Stress Corrosion," *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part II, p. 259 (1931); and other papers by McAdam listed in the references in the above paper.

(3) D. J. McAdam, Jr., "Stress Corrosion of Metals," *Proceedings*, Zurich Congress, New Internat. Assn. Testing Mats. (1931).

(4) W. E. Harvey, "Zinc as a Protective Coating Against Corrosion-Fatigue of Steel," *Metals and Alloys*, Vol. 1, p. 458, April, 1930.

(5) W. E. Harvey, "Cadmium Plating *versus* Corrosion-Fatigue. Pickling *versus* Corrosion-Fatigue," *Metals and Alloys*, Vol. 3, p. 69, March, 1932.

(6 B. P. Haigh, "Chemical Action in Relation to Fatigue of Metals," *Transactions*, Inst. Chemical Engrs., Vol. 7, p. 29 (1929).

(7) T. S. Fuller, "Some Aspects of Corrosion Fatigue," *Transactions*, Inst. Metals Division, Am. Inst. Mining and Metallurgical Engrs., p. 47 (1929).

(8) H. S. Rawdon, "Structure of Commercial Zinc Coatings," *Proceedings*, Am. Soc. Testing Mats., Vol. XVIII, Part I, p. 216 (1918).

(9) W. H. Finkeldey, "The Microstructure of Zinc Coatings," *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part II, p. 304 (1926).

(10) W. Guertler, "Structure of Galvanized Iron," *Zeitschrift für Metallographie*, Vol. 1, p. 353 (1911).

(11) H. F. Moore and Tibor Ver, "A Study of Slip Lines, Strain Lines, and Cracks in Metals Under Repeated Stress," *Bulletin No. 208*, University of Illinois Engineering Experiment Station (1930).

(12) H. W. Gillett, "The Need for Information on Notch Propagation," Correlated Abstract, *Metals and Alloys*, Vol. 1, p. 114, September, 1929.

(13) H. W. Gillett, "What Is This Thing Called Fatigue?", *Metals and Alloys*, Vol. 2, p. 71, February, 1931.

DISCUSSION

Mr. Robert Job.[1]—I have been very much interested in the paper by Messrs. Swanger and France and also in an article on cadmium plating *versus* corrosion-fatigue by Wilber E. Harvey appearing in a recent issue of *Metals and Alloys*, showing the resistance to corrosion derived from various metallic coatings.

In this connection some tests which we have been making may be of interest. Threaded steel staybolts were tested in a vibratory machine. Two were tested without coating, and two after plating thoroughly with cadmium. Water was allowed in each case to drip upon the stressed portion.

As a result of our tests we were rather surprised to find that the results upon the coated and the uncoated staybolts were about the same. In other words, no benefit appeared to be derived from the coating of cadmium. Our feeling was that, as cadmium is brittle, the coating was cracked as a result of the bending, thus allowing the water to penetrate to the steel so that little or no benefit resulted from the coating.

Our object in making the test was to determine whether some coating could be applied to a staybolt which would minimize corrosive action and thus increase the life of staybolts in a locomotive boiler.

Mr. J. R. Freeman, Jr.[2]—The authors have presented their data in unusually complete detail, so I hesitate to request a little more data, but I should like to ask them to state the length of time between the galvanizing and pickling operations and when the tests were made. I think that time interval might be of importance in relation to possible hydrogen embrittlement action.

Mr. H. S. Rawdon.[3]—For a good many years a favorite subject of discussion concerning zinc coatings has been the relative corrosion resistance of an electroplated coating and a galvanized coating. Most electroplaters like to feel that the pure zinc they put on has a greater resistance to corrosion than the somewhat contaminated zinc put on by the galvanizing process. Though not bearing on this subject, the results presented do definitely show that there is a difference in similar materials when coated in those two ways. The galvanized material appears to be definitely inferior to the electroplated material in its endurance properties. It is reasonable to suppose that the results which were obtained on the ordinary specimens in the laboratory will apply to commercial materials. That being the case, we would expect that there may be the difference of the same kind in wire that has been galvanized and wire that has been electroplated. This may, perhaps, be an important point in the near future, because the electroplating of wire is being pushed rather actively and before long we can probably buy zinc-plated wire nearly as readily as we can get the ordinary galvanized product at present. Up to date the plating of wire has been rather restricted in its scope and applied to only special products, but before long I believe the ordinary sizes and commercial grades of wire will be available in the plated form.

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[2] Technical Department, American Brass Co., Waterbury, Conn.

[3] Chief, Division of Metallurgy, U. S. Bureau of Standards, Washington, D. C.

MR. W. M. PEIRCE.[1]—One comment should be made in connection with Mr. Rawdon's remarks. The magnitude of the difference which exists between the endurance properties of the electro-galvanized and the hot-galvanized materials is probably affected by the thickness and uniformity of the alloy layer existing in the particular hot-galvanized specimens used for the test. The thicker and more non-uniform this alloy layer, the greater the difference which might reasonably be expected.

The alloy layer may be kept thin and uniform by galvanizing as soon as possible after drawing. When there is no opportunity for rusting and the pickling can therefore be reduced to a minimum and the time of immersion in the galvanizing bath is short, the alloy layer will be thin and the boundary between the alloy layer and the steel will be smooth. This is commercially accomplished in galvanizing wire to secure the best bending properties in the coating.

Being familiar with the conditions under which the samples used in this work were galvanized, I do not believe that these ideal conditions were approximated as closely as is possible in good commercial practice and I therefore feel that final conclusions should not be drawn without further data on the effect of this variable.

MR. W. H. FINKELDEY.[2]—Referring to Mr. Rawdon's remarks, I should like to point out that the differences between the fatigue performance of hot-galvanized and electro-galvanized iron wire and low-carbon steel wire are small and also that large tonnages of hot-galvanized wire are normally produced in these classes.

I should also like to ask the authors whether they can offer any explanation for the difference between the performance of the electro-glavanized and the hot-galvanized in the case of the high-carbon steel *versus* the low-carbon steel?

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[2] Metallurgist, Singmaster & Breyer, New York City.

MR. W. H. SWANGER.[1]—In reply to Mr. Freeman's suggestion, we had in mind the possibility of hydrogen embrittlement of the acid pickled specimens. Some of these specimens were put into the testing machines immediately after they had been washed and dried from the acid bath and others of the same series were tested from a week to a month after they had been pickled. If hydrogen embrittlement were a factor in causing the lower endurance limits of the pickled specimens it is reasonable to expect that the effect would have been more pronounced in the specimens tested immediately after pickling than in those tested a month or more after they had been pickled. The values obtained in the fatigue tests of a series of pickled specimens all fell on the *S-N* diagram for the series without any unusual scattering, regardless of the time after pickling at which they were tested. Hence it was concluded that hydrogen embrittlement was not a factor to be considered in these tests.

With regard to Mr. Job's remarks it is believed that the benefit imparted by a protective metallic coating to a steel subjected to simultaneous corrosion and stress will largely be lost if the stress is of sufficient magnitude to cause cracks in the coating. Probably the stresses in the tests mentioned by Mr. Job were of such magnitude.

When corrosion is not a factor and the stresses are sufficient to cause cracks in the coating, the data given in the paper indicate that it depends, to some extent at least, upon the nature of the coating and of the bond between coating and steel as to whether or not the coated steel will have a lower endurance limit than the uncoated steel. In a comparatively thin hot-dipped galvanized coating mentioned by Mr. Peirce, the brittle zinc-iron intermetallic compounds are present, although the coating as a whole would undoubtedly have better bending properties than a heavy galvanized coating. The electroplated coatings on the specimens we tested were cracked to about the same degree as the hot-galvanized coatings, but the results of the fatigue tests indicate that the damaging effect is greater when the crack is in a hard brittle layer intimately bonded with the steel than when it is in a comparatively soft and ductile layer such as an electroplated zinc coating. Hence it is believed that the lowering of the endurance limit caused by the presence of the hit-dipped galvanized coatings was not appreciably influenced by the overall thickness of the coatings.

In answer to Mr. Finkeldey's question I think that the properties of the steel itself undoubtedly were also a factor in determining the amount of damage caused by the zinc coatings. The softer and more ductile steels were less susceptible to propagation of the "notches" caused by cracks in the galvanized coatings than were the harder heat-treated steels. Therefore there was less damage to the softer than to the harder steels caused by the hot-dipped coatings.

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[1] Metallurgist, U. S. Bureau of Standards, Washington, D. C.

MESSRS. SWANGER AND R. D. FRANCE[1] (*authors' closure by letter*).—It was brought to the authors' attention by H. W. Gillett, subsequent to the meeting, that the endurance ratios (endurance limit to tensile strength) of the quenched 0.45 and 0.72-per-cent carbon steels in the uncoated condition were abnormally high. The tensile strengths of these materials had been determined on standard 0.505-in. diameter test bars. Mr. Gillett suggested that the fatigue test specimens, which were approximately only 0.2 in. in diameter were harder than the tension test specimens. We have made Rockwell hardness determinations on the reduced diameter sections of broken fatigue test specimens. The Rockwell numbers on the fatigue test specimens of the quenched 0.45-per-cent carbon steel agreed with those on the tension test bars, and the tensile strength of the fatigue test specimens could not have been much higher than the value given in Table II of the paper. The average of the Rockwell hardness numbers of three quenched 0.72-per-cent carbon steel fatigue test specimens was 45 C instead of the value 39 C obtained on the tension test bars. Hence the tensile strength of the fatigue test specimens must have been greater than the reported value of 176,000 lb. per sq. in., and the endurance ratio less than 0.70.

It is not believed that a tension test of a quenched 0.72-per-cent carbon steel determined on a specimen of the shape of a fatigue test bar would be reliable and a value for the endurance ratio of this steel in the quenched condition is questionable. Too much significance should not be placed on an endurance ratio. In a fatigue test, and more so in actual service, the surface condition of a specimen or structural member may cause quite a different safe working load from what would be expected if the endurance ratio of the material were used as a criterion.

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SOME FACTORS AFFECTING THE PREECE TEST FOR ZINC COATINGS[1]

By H. H. Walkup[2] and E. C. Groesbeck[3]

Synopsis

The results of a study of some factors involved in the Preece test for testing zinc coatings on ferrous products are presented in this paper. The Preece test has been severely criticized by various authorities because of the erratic results which are sometimes obtained, although it finds a wide use, for inspection purposes, in determining the uniformity of the coating. This study was undertaken with the aim of ascertaining the underlying causes for the reported erratic results.

A prominent characteristic of these erratic results is the formation of false end points, that is, the appearance of adherent copper on the zinc coating before the underlying base metal has been reached. The causes producing these false end-points may be grouped under three general classes: (1) variation in nature of zinc coating, (2) variation in copper sulfate solution employed, and (3) manipulation. False end points were obtained by various experimental methods.

The results of two series of experiments carried out with hot-dip galvanized, "galvannealed," zinc, iron, and steel wire specimens are shown diagrammatically.

By investigating the effects produced by variations in the potential and pH value of different types of zinc coatings and copper sulfate solutions, it was determined that false end points can be formed by the lodgment of copper particles on the specimen surface. The effects of certain variables on the adherence of copper deposits on the iron or steel base at the true end points were also investigated.

Introduction

The Preece, or copper sulfate dip, test has been severely criticized, since the results obtained in testing zinc-coated products may be quite erratic and therefore misleading.[4, 5, 6, 7] This test consists essentially

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[1] Publication approved by the Director of the Bureau of Standards of the U. S. Department of Commerce.

[2] Junior Scientist, U. S. Bureau of Standards, Washington, D. C.

[3] Metallurgist, U. S. Bureau of Standards, Washington, D. C.

[4] W. A. Patrick and W. H. Walker, "Method for Testing Galvanized Iron to Replace the Preece Test," *Industrial and Engineering Chemistry*, Vol. 3, p. 239 (1911).

[5] W. E. Hughes, "Modern Electroplating," p. 80, H. Frowde and Hadden and Stoughton, London (1923).

[6] W. M. Peirce, "The Preece Test for Zinc Coated Materials," *The Iron Age*, Vol. 114, p. 199 (1924).

[7] H. Bablik, "The Preece Test," *The Metal Industry* (London), Vol. 28, p. 369 (1926).

of immersing samples of the galvanized material in a copper sulfate solution for periods of one minute each until bright adherent copper is obtained. The formation of this copper deposit, which indicates that the iron beneath the coating has been exposed, is taken as the end point. After each immersion period, the sample is washed under running water and the copper deposit lightly rubbed off. The solution is prepared by dissolving 36 g. of copper sulfate crystals in 100 parts of water and adding sufficient cupric oxide to neutralize any free acid. After the solution has been filtered or decanted, its specific gravity is brought to 1.186 at 18°C., which temperature should be maintained during the test.[1]

This test is based on the assumption that the weights of coating dissolved in one minute for various galvanized materials are comparable, and hence a relation between the thickness on different samples can be obtained by noting the number of immersions required to produce an end point. Furthermore, a measure of the uniformity of the coating is obtained by comparing the number of immersions with the total weight or average thickness of the coating, as determined by the hydrochloric acid - antimony chloride stripping test. A uniformity test of this nature is, therefore, dependent on the rate of solution of the coating.

When this test was first introduced, it was believed that the results bore a close relationship to the service behavior, because it was assumed that the corrosive attack produced on the galvanized material by the copper sulfate solution and that resulting from atmospheric conditions are both electrochemical in nature. This general belief and the great simplicity of the test procedure led to wide acceptance of this method for testing galvanized coatings. Difficulties were, however, encountered, and in 1911 this Society, through its Committee A-5 on Corrosion of Iron and Steel, expressed its unanimous opinion that the method is unreliable and should be abandoned entirely as a basis of specification covering galvanized sheet and plate.[2] It, nevertheless, admitted that the Preece test has the advantage of being a quick and simple method for testing galvanized wire, especially for inspection purposes, and that it gives comparable results if properly applied. Despite such condemnation, this test has continued to be widely used, even by large public utility organizations, especially in connection with specifications for wire and electrical construction materials.

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[1] Appendix to Standard Methods of Determining Weight of Coating on Zinc-Coated Articles (A 90 - 30), 1930 Book of A.S.T.M. Standards, Part I, p. 390.

[2] Report of Committee A-5 on Corrosion of Iron and Steel, *Proceedings*, Am. Soc. Testing Mats., Vol. XI, p. 100 (1911); also Vol. XVII, Part I, p. 143 (1917).

The reported difficulties, sometimes encountered, may be classed under three general heads: (1) variations in the solution rate of the coating, (2) appearance of adherent copper on the coating, and (3) non-adherence of the copper deposit on the exposed steel base.

If there are areas of unequal potential on the surface of a specimen, during immersion in a copper sulfate solution, the areas having the higher (more negative) single potentials act as anodes and the metal in these areas goes into solution, while the areas of lower potentials act as cathodes. If the potential difference between such areas is high enough, copper deposits on the cathode in an amount equivalent to the zinc dissolved. The adherence or non-adherence of the copper deposit depends upon such factors as the potential difference and resultant current density, nature of the surface, $CuSO_4$ concentration, pH value, time, temperature, degree of agitation, and polarization characteristics of the solution.

Bablik,[1] following the earlier work of Peirce,[2] reported that the variations in the solution rate of galvanized coatings is related to the potential of the coating when immersed in a copper sulfate solution. He stated that the iron content of galvanized coatings varied from 1 to 10 per cent, and showed that both the potential and loss in weight per immersion decrease with an increase in iron content. His data, therefore, explain why comparable results can be obtained with coatings of a similar type but not with those of different types.

A study of some of the main variables involved in the Preece test was made at the U. S. Bureau of Standards to ascertain the cause of the reported irregularities. In this paper the results of this study have been summarized. A more detailed presentation of the results. including data on the effect produced by concentration, temperature and oxidizing-agent content of the copper sulfate solution, in another publication at a later date is contemplated.

The term "galvanized" as used in this paper applies, in a general sense, to metals coated with zinc by any method, such as hot-dip galvanizing, "galvannealing,"[3] electroplating, sherardizing and metal-spraying. Wires of commercially pure zinc, iron and soft steel were also included in the experimental work, as these materials were found suitable to study the effects of certain factors. The term "rubbing" refers to removal of the deposit under appreciable frictional pressure such as that obtained with a pencil eraser, and "wiping" to removal under less frictional pressure, such as produced with a cotton swab. The recorded pH values were obtained with a quinhydrone electrode.

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[1] *Loc. cit.*

[2] *Loc. cit.*

[3] "Galvannealing" is a modification of the hot-dip process, which includes annealing of the zinc-coated metal.

CONDITIONS LEADING TO FORMATION OF FALSE END POINTS

The causes which have been found to contribute to the formation of false end points (appearance of adherent copper before the iron or steel base has been exposed) are grouped under three heads: (1) variation in nature of zinc coatings, (2) variation in copper sulfate solution, and (3) manipulation during the test. Three types of false end points were obtained experimentally; one caused by direct electrochemical deposition and the other two by the mechanical lodgment of spongy copper particles on the zinc coat. One of the two mechanical types was caused by the lodgment of the particles in recesses formed in the coating by the action of the solution, and the other by the squeezing of the particles into an adhesive plastic layer of basic zinc salts which formed between the coating and spongy copper deposit. This last type appears to be an important source of the false end points reported for the Preece test.

Specimens of electroplated, hot-dip galvanized, galvannealed and zinc-sprayed wire were exposed to atmospheres of steam and steam-CO_2 mixture for two days, whereby a white corrosion product was formed on the surface of the wires. When tested by the Preece test, dark adherent copper was found, after cleaning, on areas which were covered with corrosion products. These specimens also lost less in weight during the first immersion than those specimens without corrosion products, a result which is in agreement with that of Peirce. The effect of soap, oil, tin, lead and an electrical-conducting paint (graphite-rubber cement) applied to the zinc coating was also tested, but only the last two gave false end points. It was also found that false end points of a somewhat similar nature could be obtained by rubbing a zinc wire during immersion in, or after removal from, certain $CuSO_4$ solutions. A false end point of an electrochemical type, which is adherent, sometimes forms at the "water line" in certain solutions.

It was noticed that a thin, black, adherent film sometimes remained on the galvanized coating after the spongy copper deposit had been removed. The results obtained in various experiments clearly indicated that it was easy for copper particles to be squeezed, during the wiping, into this dark adherent film and that the presence of such a film was favorable to the formation of false end points. This black deposit was isolated and found, by microscopic examination, to be a white amorphous substance containing fine particles of metallic copper and black copper oxide. The material was also found to be quite plastic when tested with a sharp-pointed tool. Although no chemical analysis of this substance was made, it is believed to consist

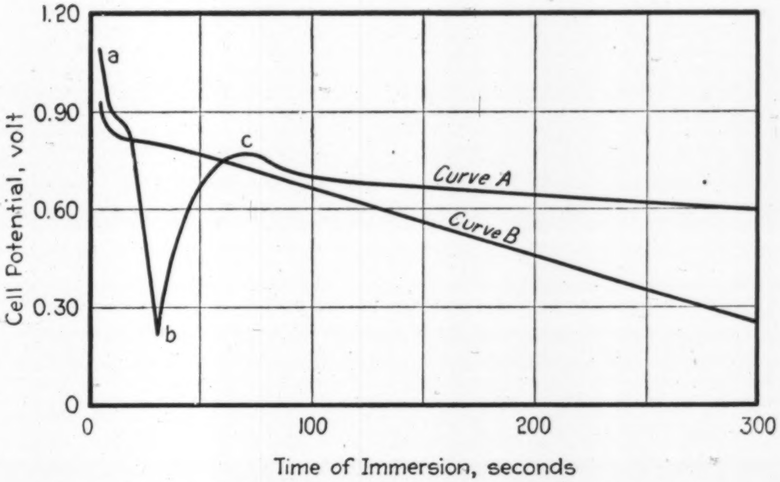

FIG. 1.—Variation in Potential with Immersion Time of Galvanized and Zinc Wire Specimens.

The portion *abc* of curve *A* is the "potential dip."

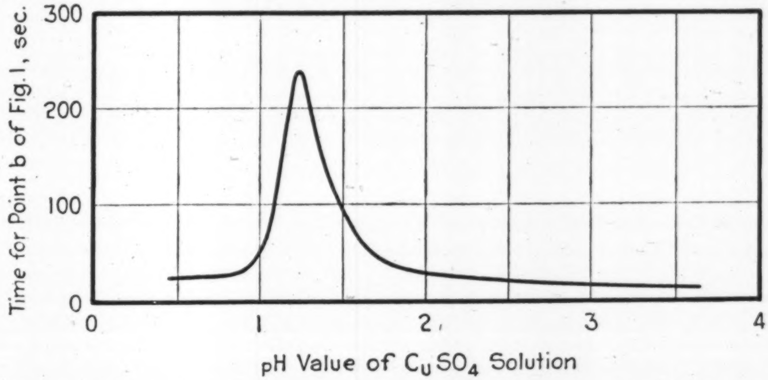

FIG. 2.—Effect of pH Value of $CuSO_4$ Solution on Time Required to Reach Minimum Potential (*b*, Fig. 1) with Pure Zinc Coatings.

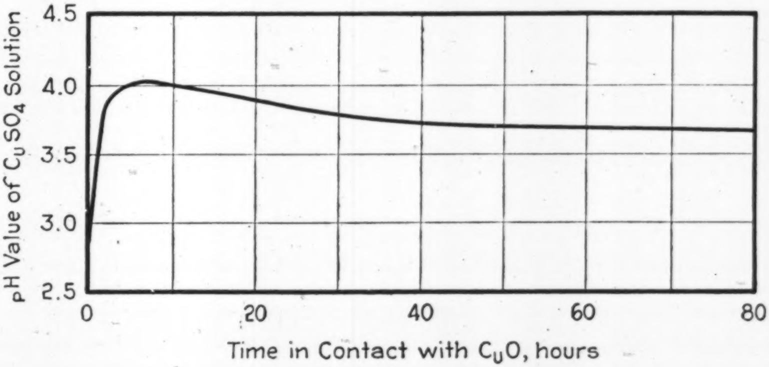

FIG. 3.—Change in pH Value of Preece Test Solution as Produced by Time of Contact with CuO.

of basic zinc salts, such as $3\ ZnO \cdot ZnSO_4 \cdot x\ H_2O$.[1] (Also see end of next section.) The formation of these salts is thought to be due to the presence around the zinc-coated wire of a liquid film whose pH value is higher than that of the body of the solution.

The mechanical lodgment of copper particles on the surface of the specimen can also occur when the black deposit is absent. While this condition is not present in the Preece test, experiments have shown that $CuSO_4$ solutions treated to give high and low pH values (above 7 and below 0.5, respectively) attack the surface sufficiently to allow lodgment of the copper particles. When an excessively high potential is applied between the zinc and solution (by an external e. m. f.), the surface is also badly attacked.

EFFECT OF VARIATIONS IN THE COPPER SULFATE SOLUTION ON THE SPONGY COPPER DEPOSIT FORMED ON ZINC AND ZINC-IRON ALLOYS

Since it was shown that the presence of the dark plastic material in the spongy copper deposit is a factor in the formation of false end points, efforts were made to control this factor.

By approaching this problem from an electrochemical standpoint, it was determined that variations in either the solution or zinc coating could produce an effect which influences the adherence of this dark material. This effect is manifested by a dip in the cell potential with time, and is illustrated by the portion *abc* of curve *A*, Fig. 1, which is referred to as the "potential dip." This curve is representative of a large number of experimental curves.

NOTE.—The data for the potential-time curves similar to *A* and *B* in Fig. 1 were obtained by using a variety of galvanized and zinc wire specimens as anodes and a copper sulfate solution modified by the introduction of selected acids, bases, salts and various organic reducing agents as the electrolyte in the cell: copper wire | solution | specimen, with the electrodes placed about 2 cm. apart. A 25,000-ohm voltmeter, provided with a 0 to 2.5 volt scale, and a stop-watch were employed for securing the potential-time data.

It was found that in the Preece test this dark material could be easily wiped off if a well-defined dip, such as that shown in Fig. 1, is completed within the immersion time of the specimen, and that it remains adherent if the dip is not completed within this time. By testing specimens containing increasing amounts of iron in the coating, the potential dip can be modified until curve *A* approaches curve *B* in form; in other words, the potential dip is eliminated from those coatings which have a lower zinc content. Thus, in a Preece test solution, curves similar to curve *A* are obtained with electroplated materials, while curves similar to curve *B* are characteristic of galvannealed materials. Furthermore, when testing galvanized coatings of high zinc content, if the pH value of a Preece test solution is lowered by adding H_2SO_4 the time required to reach the minimum potential value, represented by point *b* (Fig. 1), can be changed, as illustrated by Fig. 2. This figure shows that the potential dip time increases to a maximum and then decreases as the acid content of this solution is increased. It is evident from these observations that both the composition of the solution and the iron content of the coating exert an influence on the adherence of the dark plastic material and hence, on the tendency to form false end points.

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[1] I. M. Kolthoff and T. Kameda, "The Hydrolysis of Zinc Sulfate Solutions, Solubility Products of Hydrous Zinc Oxide and the Composition of the Latter Precipitated from Zinc Sulfate Solutions," *Journal*, Am. Chemical Soc., Vol. 53, p. 832 (1931).

In these experiments, efforts were made to prevent the formation of false end points caused by the presence of the dark plastic material. No satisfactory chemical or electrochemical method was found, but the removal of this dark material by rubbing it off with a soft pencil eraser proved to be a practical remedy.

The Preece test solution fulfills the requirement for the completion of the potential dip within one minute, when it is used for testing coatings of high zinc content, but not for those of low zinc content. The solution pressure of zinc in the low-zinc-content coatings is not sufficient to produce the potential dip.

None of the solutions tested produced both a potential dip within one minute and an adherent copper deposit on the exposed iron or steel base on every type of galvanized coatings.

The pH values of a given $CuSO_4$ solution and its action on different galvanized wires were determined at different intervals after the solution was made up. This solution was prepared according to the Preece test specifications,[1] by using c. p. $CuSO_4 \cdot 5\ H_2O$, CuO and distilled water. Figure 3 shows the relation between the pH value and the time of contact with the CuO. The pH value of the solution increased to a maximum during the first period of contact, due to the neutralization of the free acid, and then gradually decreased with the formation of an insoluble white precipitate, which is believed to consist of basic copper sulfates, such as $CuSO_4 \cdot 2\ CuO \cdot 2\ H_2O$.[2]

A solution that had been in contact with CuO in closed bottles for two months and that had a pH value of 3.6 and contained a white precipitate, produced a copper deposit on the exposed steel of galvanized wires, which was non-adherent after a 1-minute immersion. However, good end points were obtained by adding varying amounts of H_2SO_4 or H_2O_2 to this solution. A solution that had been exposed to the atmosphere and kept in contact with CuO for a shorter time (with the formation of a white precipitate) produced an adherent copper deposit. The difference in the behavior of these two solutions may be due to a difference in the content of cuprous compounds.

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[1] Appendix to Standard Methods of Determining Weight of Coating on Zinc-Coated Articles (A 90 – 30), 1930 Book of A.S.T.M. Standards, Part I, p. 390.

[2] S. W. Young and A. E. Stearn, "The Basic Copper Sulphates," *Journal*, Am. Chemical Soc., Vol. 38, p. 1947 (1916).

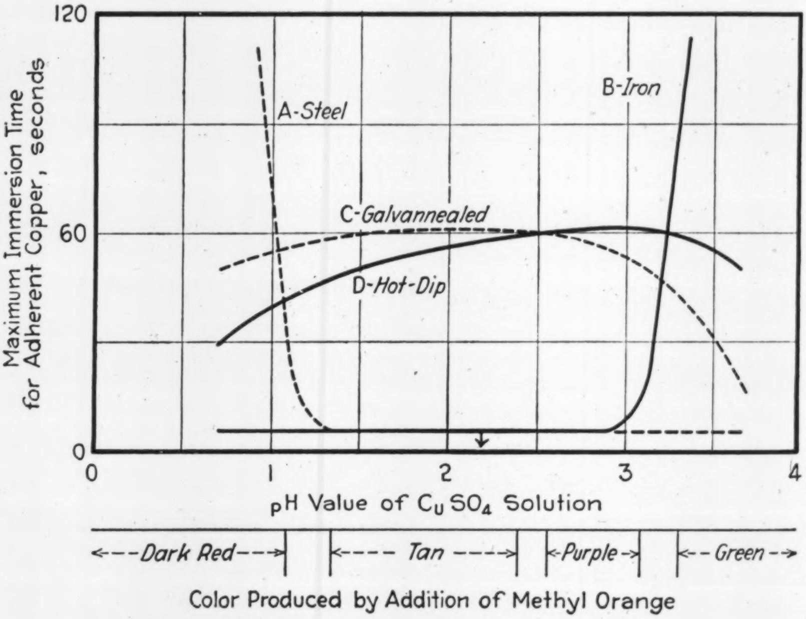

FIG. 4.—Effect of Immersion Time, pH Value and Galvanized Coating on Copper Adherence on Iron and Steel.

The time position of the horizontal line is below the 5-seconds level. The blank spaces in the color scale represent transition zones.

VARIATION IN ADHERENCE OF DEPOSITED COPPER ON THE IRON OR STEEL BASE

It has already been pointed out that, in addition to the erratic appearance of adherent copper on the coating, the Preece test is also subject to conditions which produce non-adherent copper on the exposed iron or steel base. In order to measure the effects of different variables on the degree of adherence of copper on iron and steel, a test was developed in which the degree of adherence was held approximately constant and the effect of one variable was obtained in terms of another. The roughly constant degree of adherence was attained by subjecting all deposits to the same frictional forces produced when the deposit was wiped "very hard" with a dry cotton swab. The reference variable selected was the maximum immersion time during which the deposit remained adherent, as it is known that the copper deposits of this type tend to become less adherent with increasing immersion time.

Curves *A*, *B*, *C* and *D* in Fig. 4 show the observed relations between time of immersion, pH value of $CuSO_4$ solution, and four types of wire materials (low-carbon steel, commercially pure iron, hot-dip galvanized, and galvannealed, the last two of which had a portion of the coating removed so as to expose the underlying base). In order to avoid effects of other possible variables, the following procedure was used:

1. The maximum immersion time in any given solution during which the copper deposit remained adherent, was determined by immersing several specimens of the same material successively. Each specimen was immersed only once in order to hold constant the effect of the zinc coating (on the hot-dip galvanized and galvannealed wires) surrounding the copper deposit.
2. Each specimen was cleaned before immersion by rubbing with No. 400 Aloxite paper, immersing in a 10-per-cent H_2SO_4 solution for 5 to 10 seconds, washing in H_2O, and wiping dry with a dry cotton swab.
3. Immediately after drying the specimen was immersed in the given solution which was at room temperature.
4. The desired pH values were obtained by adding the required amounts of H_2SO_4 or NaOH to portions of a solution saturated with respect to $CuSO_4 \cdot 5\,H_2O$.

In Fig. 4 the maximum points of curves *C* and *D* lie approximately between pH values 2 and 3; that is, for the conditions used, the copper deposits formed within this range are more adherent (as estimated from the immersion time factor) after a 1-minute immersion than those formed at a higher or lower pH value. These high points, however, are due to the influence of the zinc coatings; if the coating were entirely removed previous to immersion, the maximum immersion time (below 5 seconds) for the copper deposit to remain adherent in solutions with pH values from 2 to 3 would be along the horizontal level. Figure 4 also shows that better copper adherence is obtained for galvannealed wires than for hot-dip galvanized wires in solutions with low pH values while the reverse is true for high pH values. By decreasing the immersion time from one minute to 30 seconds, the chance for the copper deposit to be adherent on both wires is increased.

As illustrated in Fig. 2, the potential dip time (curve *A*, Fig. 1) is less at a low or high pH value than at an intermediate pH value. The chances for the formation of false end points would, therefore, be greater in this intermediate range.

These experiments also indicated the following:

1. Solutions of high pH value (3.5) do not show as great a tendency for surface pitting of the specimen as solutions of low pH value (0.5), but that the tendency for precipitation of basic copper sulfate is greater in the solutions of high pH value.

2. An increase in the temperature of the $CuSO_4$ solution causes an increase in the solution velocity of the zinc coating and a decrease in the adherence of the copper deposit.

3. Two saturated $CuSO_4$ solutions having respectively a pH value of 1 and 3.6 were diluted with an equal volume of water. Adherent copper was obtained on steel wire specimens after a 1-minute immersion in the low pH solution before and after dilution but not from either of high pH solutions.

4. If salts containing common ions, such as Na_2SO_4, are added to a solution of intermediate pH value, the time during which the copper deposit remains adherent is increased.

5. The presence of chlorides or of nitrogen oxides in the $CuSO_4$ solution causes the copper deposit to be non-adherent.[1]

A simple method for determining the pH value of the $CuSO_4$ solution was developed by adding two drops of a saturated aqueous solution of methyl orange to a 1-ml. portion of the $CuSO_4$ solution in a test tube of small diameter. After the mixture is well shaken and let stand for five minutes, the color of the liquid is determined by viewing in bright daylight. The observed pH color scale, given in Fig. 4, was obtained by adding H_2SO_4 or NaOH to saturated $CuSO_4$ solutions. It should be noted that a blue color is obtained with this methyl orange test in the pH range 3.1 to 3.3 and a green color above this range. However, when a high pH value is obtained by using copper oxide instead of NaOH and by leaving the solution in contact with it for a sufficiently long time, the color at pH 3.6 will be blue, and at higher pH values green.

POSSIBLE APPLICATIONS OF RESULTS TO THE PREECE TEST

The above results may be applied in the Preece test as follows:

Clean the specimen, if any corrosion products are present, by rubbing it with fine sandpaper; immerse it in the $CuSO_4$ solution (100 ml. for each wire specimen) for one minute; remove the spongy copper by first holding the specimen under a strong stream of water, and then wiping it with a cotton swab; and finally rub it with a soft pencil eraser until the surface appears bright. Repeat the procedure until the true end point is indicated by the appearance of an adherent copper deposit which has a characteristic bright color before and after rubbing. The area of this end point will increase in the next following immersion. If undue pressure is applied in rubbing, the copper which characterizes the end point may be removed.

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[1] E. P. Schock and D. J. Brown, "An Electroanalytical Method for the Determination and Separation of the Metals of the Copper-Tin Group," *Journal*, Am. Chemical Soc., Vol. 38, p. 1660 (1913); also A. J. Engelenburg, "Elektroanalytische Methoden zur Bestimmung von Metallen aus Salzsaurer Lösung," *Zeitschrift analytische Chemie*, Vol. 62, p. 257 (1923).

The composition and preparation of a suitable $CuSO_4$ solution involves both theoretical and practical considerations. In this paper no definite solution is recommended, but three are suggested for further consideration.

1. If the Preece test solution is used, its pH range can be estimated by the appearance of a green color in the methyl orange test. This solution has the advantage that the relation between the number of 1-minute immersions and the weight of coating has been approximately determined. The adherence of the copper deposit produced by this solution is influenced by the zinc content of the coating surrounding the bared steel. The uncertain pH value of this solution is a disadvantage, since non-adherent copper will form on the bared steel base if this value becomes too high. (See Fig. 4 and discussion.)
2. A solution with a more closely controlled pH value that gives good end points can be prepared by the following procedure. Thirty-six grams of $CuSO_4 \cdot 5H_2O$ and 2 g. of solid Na_2SO_4 are dissolved in 100 ml. of distilled water. The pH value is adjusted by adding a sufficient quantity of 2-per-cent NaOH solution to cause a color change from purple to blue-gray in the methyl orange test (about pH 3.1). The temperature of the solution, at the time of test, should be about 20°C. The adherence of the copper deposit formed by this solution at the true end point is also affected by the zinc content of the surrounding coating.
3. A 30-second immersion and a solution temperature of 10°C. will give good end points with a saturated $CuSO_4$ solution to which sufficient H_2SO_4 has been added to produce a color change from tan to dark red in the methyl orange test (about pH 1.1). In this method, the influence on the adherence of the deposited copper exerted by the zinc content of the surrounding coating is lessened. False end points may be formed in testing iron-zinc alloys, but this difficulty can be eliminated by rubbing with a pencil eraser.

In any method, the solution employed should be kept in a bottle provided with a small opening to permit access to the atmosphere, and its pH value should be checked from time to time by the methyl orange test.

Depolarizers should be carefully excluded from the solution at all times, since their presence has been shown to cause non-adherent copper. The presence of chlorides in the $CuSO_4$ solution may be detected by the formation of a white precipitate when silver nitrate is added to a portion of the solution.

DISCUSSION

Mr. C. L. Hippensteel[1] (*presented in written form*).—The authors have made a valuable contribution to a theoretical understanding of the deficiencies of the Preece test. While this information indicates conditions which must be controlled to obtain consistent results and eliminate false end points, the fact remains that there are certain conditions which limit the field of its usefulness. The results obtained with the test can be considered only qualitative at best. The limitations of the test are given in the paper and adequately supported by theory. The more detailed presentation of data promised by the authors should arouse considerable interest.

Mr. A. R. Small.[2]—I should like to comment concerning the significance of the Preece test from the point of view of an inspection authority. Part of my work for a good many years was the direction of the factory inspection work of the Underwriters' Laboratories on electrical conduits. These are coated either by the electroplating or the sherardizing or the hot-dip process. A rough control was run under my supervision on some newly made samples of conduit sent to Chicago by the factory inspectors. The samples were carefully tested for the amount of zinc per square foot. The outcome of the application of the Preece test was determined and recorded, and then the samples were placed on the roof exposed to Chicago atmosphere under identical conditions. Charts were made, covering a long period of years, of the relative resistance or capacity of the coating to protect the base steel from atmospheric corrosion. Roughly speaking we found that 0.1 oz. per sq. ft. of zinc was equivalent to one year's protection in the Chicago atmosphere, and that one dip in the Preece test was equivalent to 0.1 oz. per sq. ft. That was true with respect to coatings electroplated in a commercial way up to 0.275 to 0.450 oz. per sq. ft.

There were noticeable variations in the results obtained from the Preece test on products coated by the sherardizing method and notable unexplained variations in results for sherardizing and electroplating as compared with the hot-dip process, but my general impression is that the Preece test made at the factory for the acceptance of production has about the same accuracy—limits of accuracy—as indicated. Perhaps the precision is in the order of an ordinary yardstick graduated to eighths of an inch as compared with a millimeter scale. If you are looking for precision, you perhaps should not depend on the Preece test at all. If you are looking for a rough means of acceptance, the Preece test is very useful. And, as I have said, our experience on this one type of product is that a minute's dip is about the equivalent of 0.1 oz. per sq. ft. and about the equivalent of a year's exposure in the Chicago atmosphere.

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[1] Member of Technical Staff, Bell Telephone Laboratories, Inc., New York City.

[2] Vice-President, Underwriters' Laboratories, New York City.

MR. W. H. FINKELDEY.[1]—I wish to congratulate the authors of this paper on having done a real job in clearing up many points which must have bothered those who have studied the peculiarities of the Preece test in the past. The authors have called attention to false end points produced by such films as oil, soap, electrical conducting paint and corrosion products which may be found on the surface of zinc-coated articles. I interpret their remarks to mean that these false end points represent premature failures; in other words, early deposits of copper. I have noticed on several occasions deposits of copper after the second or third dip on heavily coated galvanized structural steel at those points where rust stains had been deposited by water dripping from ungalvanized, corroded, rusty steel directly above it. The copper deposit was fairly continuous and adherent, sufficiently so in one case to permit making a microsection which clearly showed a copper deposit overlying a heavy zinc coating. I have also noticed on numerous occasions, where hot-galvanized articles are heavily coated with smooth, adherent deposits of zinc corrosion products produced by natural weathering in the atmosphere, that the solution of the zinc coating is unduly retarded, resulting in a serious postponement of the end point. The dips that a given weight of coating would normally stand were frequently doubled, and in some cases even trebled, by the presence of these smooth, adherent, zinc corrosion products.

MR. F. F. FARNSWORTH.[2]—There is one consideration of the Preece test that has not been stressed which I believe to be of real importance to most of us interested in galvanized coatings. We have gradually come to realize that the usefulness of the Preece test is limited to an evaluation of the uniformity of the coating. The majority of us think, I believe, that it can tell us little about the thickness of coating and useful life of the coated product. The data given will bear me out in emphasizing the important part played by the type of coating, whether electroplated, galvanized, or other type in determining the rate of removal of zinc per dip and consequently the number of dips a coating of a given thickness will withstand.

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[1] Metallurgist, Singmaster & Breyer, New York City.

[2] Telephone Engineer, Bell Telephone Laboratories, Inc., New York City.

In the revised specifications for galvanized wire and wire products which are being prepared by the Society's Committee A-5 on Corrosion of Iron and Steel, we take particular pains to emphasize that the Preece test shall be used to determine the uniformity of coating only, and that it shall not be used as a weight of coating test. By so doing, we point out, at least inferentially, that we do not consider the results of the test a true measure of the life of the coating.

In using the Preece test to determine uniformity, I think we should caution that only the weakest spot in the coating is exposed. If a really uniform coating were being sought by this test, I think it would be necessary to specify that, after the coating has failed (showing an exposed steel portion) on a certain dip, at least 75 per cent of the total area of the base metal should be exposed on the next succeeding dip. At best, it seems that considerable interpretation of the test is necessary before we can accurately predict the uniformity of a zinc coating.

MR. SAMUEL EPSTEIN.[1]—How many dips can be made; how many samples can be tested before the solution is spoiled?

MR. H. S. RAWDON.[2]—The authors recommend one sample for each volume of solution taken. The only thing I would say in closing is that this work is not finished; there are several other variables that are still under study, and the final publication will be considerably longer and more detailed than the one given here. It is hoped that, as a result of this study, it will be possible to recommend a procedure that will be somewhat more satisfactory than the test in use today that is so often misused. I think the fact is now well established that the present test is not suitable for all types of coatings and should not be so used. Some regard must be had for the type of coating before the test is applied.

MESSRS. H. H. WALKUP[3] AND E. C. GROESBECK[4] (*authors' closure by letter*).—The variation in behavior of different types of zinc coatings when tested by the Preece test has been emphasized in the discussion. In the paper, time-potential curves are given to show that a difference exists in the solution of zinc and iron-zinc alloys. Since the paper was presented, a further study of these reactions was made and it is now believed that the potential-dip is a result of the formation of gelatinous zinc compounds and the transformation of these gelatinous compounds into crystalline compounds. For simplicity, the reaction of zinc hydroxide can be considered.[1] This explanation for the potential-dip stresses the importance of secondary reactions on both the yield of plastic material and solution rate of the galvanized coating.

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[1] Metallurgist, Battelle Memorial Inst., Columbus, Ohio.

[2] Chief, Division of Metallurgy, U. S. Bureau of Standards, Washington, D. C.

[3] Junior Scientist, U. S. Bureau of Standards, Washington, D. C.

[4] Metallurgist, U. S. Bureau of Standards, Washington, D. C.

Mr. Finkeldey's observations on the effect of iron rust and white zinc corrosion products are of interest and stress the importance of having a clean specimen surface. No definite answer can be given to Mr. Epstein's question because no definite reaction requirements, such as weight loss per dip, etc., are given in the specifications. It has been found, however, that increasing dilution causes an increase in the tendency to form false end points, decreases the weight loss per immersion, and (because of the variation in pH value allowed) causes either an increase or decrease in the maximum immersion time for adherent copper at the true end point. In practice, 8 in. of wire has been dipped 1 to 6 times in 100 ml. of solution.

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[1] Oskar Klein, "Über die Löslichkeit von Zinkhydroxyd in Alkalien," *Zeitschrift für anorganische Chemie*, Vol. 74, p. 157 (1912).

CONTROLLED DATA FROM AN IMMERSION TEST

BY R. F. PASSANO[1]

SYNOPSIS

It has previously been reported that there are many factors which influence the amount of corrosion taking place under water. In this study, it was found that there are seven essential external factors: temperature, oxygen concentration, velocity, type of water, area of specimen, surface condition of specimen, and time of test. With these held at definite values using well water from the Miami Valley, it was demonstrated that the resulting data did not vary significantly in a series of tests. It was necessary to use modern statistical theory to show these things. When the essential conditions had been established, the time of test was purposely varied while the other factors were maintained, and it was found that the average loss of weight was apparently proportional to the logarithm of time over the interval investigated.

The corrosion literature is largely devoted to theory and discussion of it, conclusion and implication. Too often the data are given in a radically abbreviated form or as summary curves indicating a relationship between two variables. Actually, the data are the evidence, and it should be our aim to go from the data directly to a conclusion. If the data are good, the conclusion is usually obvious. If the data are not good, there is not much to be said for the conclusion:

1. If it follows the evidence, it is probably unreliable, and,
2. If by some good fortune the conclusion is correct, it is not the result of the evidence as it stands.

Before one can say that two things are related in a definite way, it is necessary to show that all variables other than the two under investigation have been fixed, which is the same as saying that the observed variation is no more than should be left to chance.

Many of the data from corrosion tests are open to serious criticism for the reason that the effects observed have been due to extraneous causes rather than the one which was investigated. It is the exception to find an investigation in which the same test has been performed in the same way a sufficient number of times to know that the cause system was constant. It is true that one expects even consistent results to vary, but they will vary within definite limits. The problem of investigating data to determine whether they are consistent with the premise that the causes have not changed during the tests, and, the problem of calculating the limits within which "good" data may be expected to vary, is a problem which rightly belongs in the field of modern statistical theory.[1]

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[1] Research Engineer, Research Laboratories, The American Rolling Mill Co., Middletown, Ohio.

It is not the object of this paper to discuss statistical theory but it is the object of this paper to show what the essential conditions of the tests are and to show data taken under these conditions. Statistical theory is a tool, a "yard stick," which, if used kindly, will tell whether one should be satisfied with the data at hand. To avoid controversy in so far as possible, the relationship between time and extent of corrosion, as measured by loss of weight, in an immersion test has been considered as the goal.

All of the values given here were obtained in well water from the Miami Valley, using specimens of open-hearth iron. The temperature of this water as it comes from the well is about 15° C. Measurements of pH value, alkalinity, total solids, etc., do not show appreciable variation from sample to sample. The dissolved oxygen concentration is practically constant at 10 p.p.m. The velocity of water past the specimens was maintained at 100 cm. per minute by measuring the volume of water used in the test. The average of measurements of these properties is shown below for convenience:

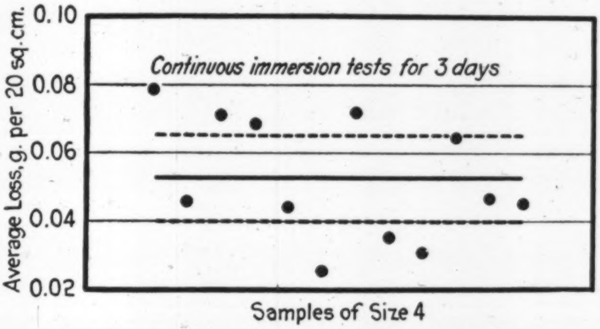

FIG. 1.—Continuous Immersion Tests for 3 Days.

Temperature	14.8° C.
Dissolved oxygen	10.2 p.p.m.
Alkalinity (as $CaCO_3$)	334.0 p.p.m.
pH value	7.5
Velocity	100.0 cm. per min.

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[1] W. A. Shewhart, "Basis for Analysis of Test Results of Die-Casting Alloy Investigation," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part I, p. 200 (1929); also "Economic Control of Quality of Manufactured Product," p. 304, D. Van Nostrand Co., Inc., New York City (1931).

In so far as the author is familiar with the methods for the analysis of data which have been described by Doctor Shewhart, the vocabulary and symbols in this paper conform to his usage. The paper may be regarded as an illustrative example of his philosophy of statistical control.

Naturally the first question to consider is whether the control of these external variables—temperature, oxygen concentration, type of water, velocity, time of test, and area of specimen—are sufficient. The data given in Fig. 1 were taken under these conditions and show definite lack of control, which is indicated by values lying outside the limits shown by the dotted lines. Certainly then there is at least one other source of variation.

It was suspected that surface condition was the source of variation. Some of the specimens had corroded all over while others had been attacked in spots and streaks. Any method of preparing the surface for test which would permit the piece to corrode all over should eliminate this source of variation if for no other reason than that the area actually under test would then be definite. When it was possible to produce specimens which corroded all over, the data shown in Fig. 2 were obtained; these give evidence of statistical control. Apparently, then, the specification of the following variables is sufficient for control:

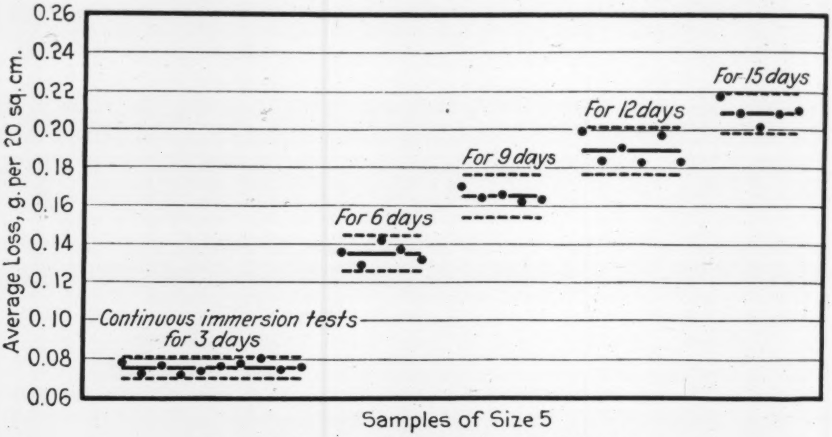

FIG. 2.—Showing Average Loss in Weight.

1. Temperature,
2. Oxygen concentration,
3. Type of water,
4. Velocity,
5. Area of specimen,
6. Surface condition of specimen,
7. Time of test.

If now the time of test is changed, maintaining all the while control of the seven other variables (those enumerated above plus the material), a relationship between time and amount of corrosion may be determined.

Table I.—Loss of Weight in Grams per 20 sq. cm.

Experiment Completed	Average Loss, $\overline{X}$, for 5 Specimens	Standard Deviation, σ, from Samples of 5 Specimens
Tests for 3 Days		
11-27-31	0.07780	0.004893
12-14-31	0.07172	0.005433
1-29-32	0.07572	0.004214
1-29-32	0.07072	0.006129
2-26-32	0.07242	0.003058
2-27-32	0.07508	0.002595
3-31-32	0.07700	0.002841
4-8-32	0.07932	0.001474
4-11-32	0.07382	0.003492
4-14-32	0.07520	0.001853
	$\overline{X}'=0.07488$	$\bar{\sigma}=0.003598$
	$3\sigma_{\overline{X}}=0.00575$	$3\sigma_{\sigma}=0.004062$
	(0.08063	(0.007660
	(0.06913	(0.0
Tests for 6 Days		
2-5-32	0.13558	0.007227
2-15-32	0.12862	0.003510
3-28-32	0.14164	0.006147
4-5-32	0.13696	0.008394
4-15-32	0.13172	0.003701
	$\overline{X}'=0.13490$	$\bar{\sigma}=0.005796$
	$3\sigma_{\overline{X}}=0.00926$	$3\sigma_{\sigma}=0.006544$
	(0.14416	(0.012340
	(0.12564	(0.0
Tests for 9 Days		
2-18-32	0.17006	0.007129
2-25-32	0.16392	0.011747
3-5-32	0.16552	0.005769
3-23-32	0.16200	0.008426
4-9-32	0.16324	0.003125
	$\overline{X}'=0.16495$	$\bar{\sigma}=0.007239$
	$3\sigma_{\overline{X}}=0.01156$	$3\sigma_{\sigma}=0.008173$
	(0.17651	(0.015412
	(0.15339	(0.0
Tests for 12 Days		
3-1-32	0.19930	0.010436
3-22-32	0.18340	0.007176
3-30-32	0.19054	0.006547
4-4-32	0.18264	0.010207
4-9-32	0.19728	0.003595
4-11-32	0.18320	0.009174
	$\overline{X}'=0.18939$	$\bar{\sigma}=0.007856$
	$3\sigma_{\overline{X}}=0.01255$	$3\sigma_{\sigma}=0.008869$
	(0.20194	(0.016725
	(0.17684	(0.0
Tests for 15 Days		
2-21-32	0.21732	0.005488
3-4-32	0.20880	0.006866
3-7-32	0.20170	0.003954
3-30-32	0.20842	0.007572
4-6-32	0.21004	0.009383
	$\overline{X}'=0.20926$	$\bar{\sigma}=0.006653$
	$3\sigma_{\overline{X}}=0.01062$	$3\sigma_{\sigma}=0.007511$
	(0.21988	(0.014164
	(0.19864	(0.0

In Table I is shown the average loss of weight on the five specimens in each test, together with the standard deviation of these values. While the averages found for the tests of a given length of time vary,

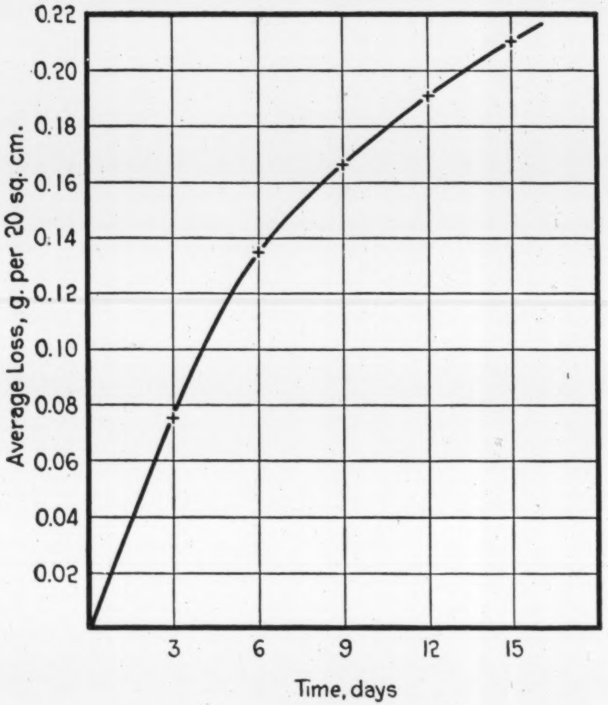

FIG. 3.—Relation of Average Loss in Weight to Number of Days.

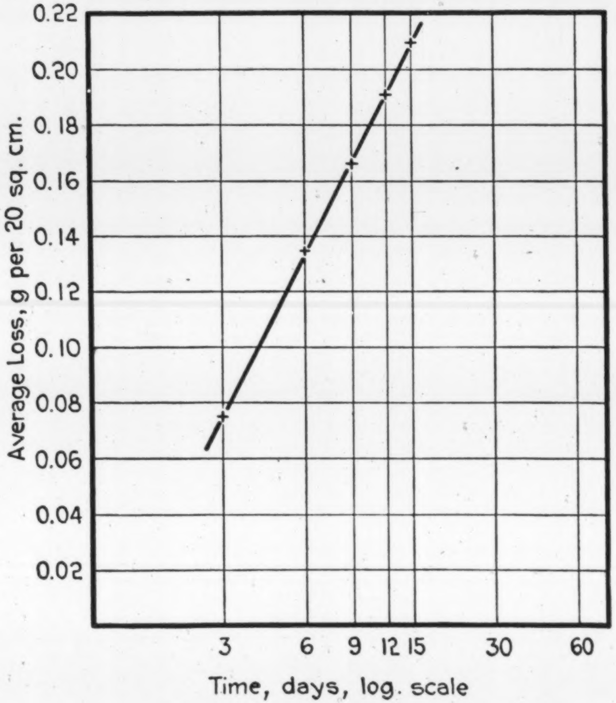

FIG. 4.—Data from Fig. 3 Plotted on Log Scale.

it is shown arithmetically in the table and graphically in Fig. 2 that this variation is not greater than can be left to chance because all values lie within the limits of the average plus and minus three times the proper standard deviation. The best value at a given time is the average of all determinations made under constant conditions. When these average values are presented graphically, Fig. 3 is the result. It is evident from an examination of this figure that the average loss of weight in these tests is not a linear function of time but may be proportional to the logarithm of time. Therefore, Fig. 4 was prepared showing the number of days of continuous immersion on a logarithmic scale.

All the points in Fig. 4 do not fall exactly on the line drawn through them, but the maximum difference between the experimental value and the line at any point is not significant (that is, the difference is not greater than that which is due to chance). The errors of the average values have been calculated and tabulated in Table II for the benefit of those interested. The error of an average, it may be recalled, depends on the standard deviation of the universe, and the number of observations.[1]

TABLE II.—SUMMARY OF DATA.

TIME OF IMMERSION, DAYS	NUMBER OF OBSERVATIONS	AVERAGE LOSS $\overline{X}'$, G. PER 20 SQ. CM.	AVERAGE STANDARD DEVIATION, $\bar{\sigma}$, $n = 5$	STANDARD DEVIATION, σ', OF UNIVERSE	ERROR OF AVERAGE, $P = 0.9973$
3	50	0.07488	0.0035982	0.00428	0.001816
6	25	0.13490	0.0057958	0.00689	0.004134
9	25	0.16495	0.0072392	0.00861	0.005166
12	30	0.18939	0.0078558	0.00934	0.005118
15	25	0.20926	0.0066526	0.00791	0.004748

NOTE 1.—$\sigma' = \frac{\bar{\sigma}}{c_2}$. $c_2 = 0.84069$ for samples of size 5.

NOTE 2.—Error x of average $= \frac{z\sigma'}{\sqrt{n}}$; $z = 3.0$ when probability $P = 0.9973$.

As the data are presented in Figs. 3 and 4, the only criterion of their goodness is smoothness (that is, the points are thought to lie on a regular or smooth curve). Such a measure of goodness is inadequate: one must *assume* that the causes have not changed during the test. Particularly when there are a small number of observations at each interval, the error at any point may be large—even though the cause system remained constant while the observations were being made—and it is a matter of opinion whether a curve can be drawn through the values, and, if so, where. When, however, the tests are conducted in such a way that criteria for constancy in the cause system can be applied and have indicated control, the investigator has confidence in his data, knowing that the measurements have been influenced by the single cause which he has varied purposely (the cause, to be sure, may be complex in nature). One's assurance in data, derived relationships, and conclusions is increased to an unbelievable degree when it can be shown that there has been statistical control. The author is convinced that when these are the conditions one is as nearly positive as it is ever possible to be in experimental work.

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[1] C. H. Humes, R. F. Passano and Anson Hayes, "A Study of the Error of Averages and Its Application to Corrosion Tests," *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part II, p. 448 (1930).

The determinations reported in this paper were made in a novel apparatus which was built in these laboratories. While it may be considered ill-advised not to have described the device, it is not really a serious omission. The important thing is that the data are statistically controlled when the conditions which have been listed above are maintained. Any apparatus in which it is possible to establish and maintain the required conditions is just as suitable as the one used in this investigation and the data from it can be compared directly with the data shown in this paper.

SUMMARY

The feature of this paper is the fact that the causes of exaggerated variations in immersion tests have been held at definite values over a period of time.

The data are statistical in nature and give evidence that they were taken under constant conditions.

With the essential conditions maintained at definite values, the time of test was purposely varied, and it was found that the loss of weight was apparently proportional to the logarithm of time over the interval investigated.

Practically all of the information contained in the raw data is shown in the summary by the average $\overline{X}'$, the standard deviation, σ', of universe, and the number of observations.

Acknowledgments.—It was explained in a footnote above that the background for this work was Shewhart's philosophy of statistical control. This paper not only marks an acceptance of his work but it may be said frankly the principles of modern statistical theory are the milestones on the road to progress in this field. The author continues to express his gratitude to Dr. Shewhart.

Under present conditions, it has been necessary to call on practically every division of these laboratories for assistance in one form or another. The author wishes to express his appreciation here particularly for the cooperation given by Messrs. O. A. Fritzsche, C. H. Humes, H. P. Munger, F. R. Nagley, and J. C. Young.

DISCUSSION

Mr. H. S. Rawdon.[1]—It is well recognized by every one who carries on corrosion tests, that surface preparation is a decidedly important factor, and I should personally appreciate it if Mr. Passano would tell us something more about the preparation of his specimens.

In any one series, will the preparation be the same throughout?

Mr. F. N. Speller.[2]—In Fig. 3 of Mr. Passano's paper, the rate of loss is plotted proportionally to the time, showing a slowing down of the corrosion with the time. This is quite in agreement with most of the immersion corrosion data. You will notice that by plotting the results on a logarithmic scale, that significant fact is lost. It would seem that we can carry mathematical analysis a little too far, although no one would question the value of such analyses. It is a fundamental fact that in nearly all corrosion tests the rate of corrosion starts at a maximum rate and then slows down with time at a rate dependent upon the nature of the metal and the environment. In the case of high-chromium steel or chromium-nickel steel, and sometimes with ordinary steels, a protective film is formed that ultimately prevents further appreciable corrosion. We must thank Mr. Passano for pointing out that there apparently is some law involved that brings these points on a straight-line logarithmic curve.

Mr. R. F. Passano[3] (*author's closure*).—The description of a specific apparatus and a specific method of preparing the surface of the test specimens were omitted from this paper because it is certain that the methods used in this investigation are not the only ones which can be employed to give results. To answer Mr. Rawdon's question more directly, the surfaces of specimens in preliminary and supplementary investigations were prepared by pickling in hydrochloric acid, sand-blasting, wire brushing, etc., and it was indicated that *as long as the specimens corrode all over*, the loss of weight is not apparently a function of the method of preparing the surface.

In the series of experiments shown in this paper, the specimens were all prepared by one method. There is no reason that I can suggest for any of the values at a given time being different. They might all have been expected to be identical. They were not, of course; they varied within definite limits, which is what one would expect if the essential conditions were held constant.

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[1] Chief, Division of Metallurgy, U. S. Bureau of Standards, Washington, D. C.

[2] Director, Department of Metallurgy and Research, National Tube Co., Pittsburgh, Pa.

[3] Research Engineer, Research Laboratories, The American Rolling Mill Co., Middletown, Ohio.

Regarding Mr. Speller's remarks on the use of a logarithmic scale, the author had hoped to avoid such a possibility by showing the observed relationship between time and loss of weight on linear and logarithmic scales side by side (see Figs. 3 and 4). Changing the scale alters the appearance of the curve, to be sure, but does not alter the significance of the data.

It is not out of place to refer to the oxidation of metals at high temperatures in connection with the process of rusting under water. Tammann[1] studied the increase in thickness of oxide layers at various temperatures between 250 and 650° C. using interference colors to measure the thickness of the films and concluded that the increase in thickness was proportional to the logarithm of time. Pilling and Bedworth[2] investigated the oxidation of metals between 300 and 1000° C. by measuring the increase in weight, or, in some cases, the change in electrical resistance of the metal. They divided metals into two classes; the oxidation of the *light metals* continued to occur in direct proportion to time, but, the oxidation of the *heavy metals* was retarded by the solution and diffusion of oxygen in the oxide. Thus, the amount of oxidation was found to be proportional to the square root of time. Any one interested in this subject will find Mr. U. R. Evans' review of it most enlightening.[3]

The number of possible combinations of variables of under-water tests is enormous. It is quite likely that the rusting process is fundamentally one of diffusion and that the loss of weight depends on the thickness and nature of the rust layer. It is certain that the rust layer increases in thickness with time, but the nature of the compounds in the rust does not necessarily remain unchanged by time, temperature, oxygen concentration, velocity, composition of water and metal. It is possible that alteration in the characteristics of the rust is the key to the time - loss of weight relationship. Without additional evidence, I personally would hesitate to apply to other conditions of immersion the logarithmic relationship between time and loss of weight found under the present conditions. In this paper, therefore, the data are presented without theoretical discussion in a way that will convey the information contained in the original observations.

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[1] *Stahl und Eisen*, Vol. 42, p. 615 (1922).

[2] *Journal*, Inst. Metals, Vol. 29, p. 529 (1923).

[3] U. R. Evans, "The Corrosion of Metals," pp. 12–19, Edward Arnold and Co., London (1924).

SOME NOTES ON MECHANISM OF DEFORMATIONS IN GRAY IRON

By J. W. Bolton[1]

Synopsis

The phenomena of "permanent set" in gray irons are due to the overstressing of certain portions of the matrix. In the initial stages of non-elastic deformation the graphite flakes probably act as voids within the matrix. Beyond a certain point they possibly act as relatively non-compressible non-tenacious inclusions.

Stress distribution in gray irons is non-uniform, and paths of greatest stress intensity usually lie between graphite flakes most closely approaching each other and where orientation is most unfavorable. With greater amounts of graphite flakes, larger size flakes, and unfavorable distribution, resistance to permanent deformation or set is lessened. Therefore susceptibility to permanent deformation is dependent on the size and distribution of graphite flakes as well as on their amount.

A case is shown where "set" increases proportionally more than does the increase in loading.

Room-temperature creep tests indicate that gray irons do not creep at room temperature when loaded to 80 per cent of their tensile strengths. This suggests that although gray iron possesses no apparent true proportional limit (because of the set phenomena) the elastic limit (or more accurately the limiting stress at which statically loaded bars will not "flow" and rupture) is somewhat above 80 per cent of the tensility and probably approaches it rather closely.

Characteristic tensile and transverse stress-strain diagrams of gray iron alloys are curved from inception—in this respect resembling those of plastic materials, that is non-elastic materials. To a physicist such diagrams suggest that sustained application of stress may result in continued flow and ultimate failure—an assumption not in accord with the known fact that gray iron castings subjected to considerable stresses over long periods remain sound and serviceable. This paper shows that certain gray irons subjected to relatively high static loads (at room temperatures) will hold up indefinitely. The apparent paradox—a metal whose stress-strain diagram resembles that of a plastic material, yet whose ultimate behavior indicates a degree of true elasticity—is discussed.

It has been known for many years that stresses applied to gray irons cause permanent deformations or set. The amount of set, in a given iron, depends on the load—the higher the load the greater the set. When a given stress is repeated the deformation is maximum for the first loading and decreases on repeated loadings, so that after a few loadings the set increments apparently approach zero. It is known in a general way that different irons show different total sets, and that the same iron when cast into sections of various sizes shows different sets for each section on test specimens taken therefrom.

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[1] Chief Chemist and Metallurgist, The Lunkenheimer Co., Cincinnati, Ohio.

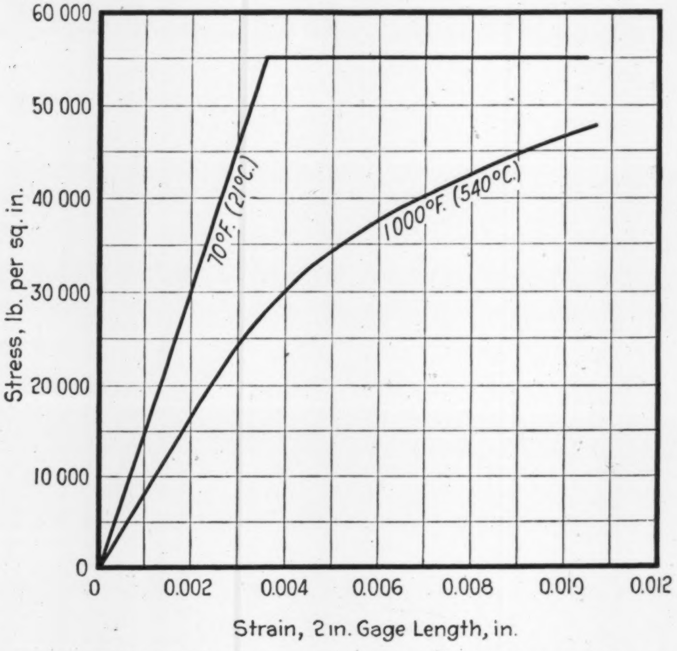

FIG. 1.—Tension Test Stress-Strain Curves for Carbon Cast Steel.

The set usually increases with increase in size of section, or inversely as the tensile strength. MacKenzie[1] advanced the hypothesis "that a large part of the set is due to some crushing of graphite flakes or to squeezing of iron grains into the flakes or voids surrounding them," and suggests that the amount of set is proportional to the amount of graphite. Sufficient elevation of temperature with a given iron and given stress also increases set.

Structurally speaking there are certain resemblances between carbon steel, gray cast iron, and white and mottled iron. Hypoeutectoid steel as cast consists of pearlite and ferrite, the proportion of pearlite increasing with carbon content up to about 0.85 per cent carbon, at which point the steel is all pearlitic. Gray iron usually consists of a largely pearlitic matrix (which usually has some ferrite and steadite in it, depending on the amount of combined carbon present and on the percentage of phosphorus) throughout which many graphite flakes are dispersed. These soft, easily distorted, graphite flakes may occupy 8 to 10 per cent of the volume or space within the metal. That is, in some respects the matrix of gray iron resembles the matrix

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[1] J. T. MacKenzie, "Elastic Properties of Cast Iron," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 94 (1929).

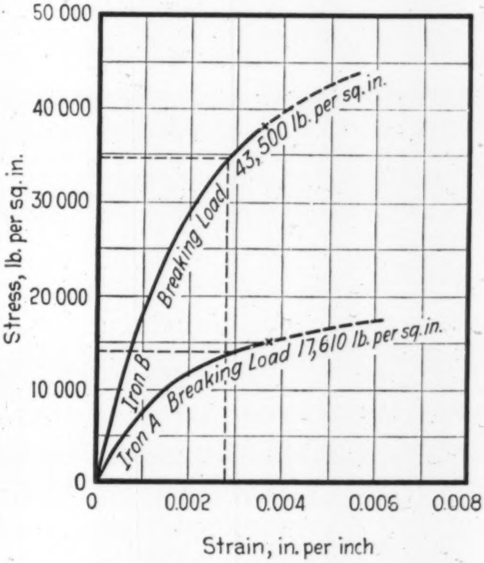
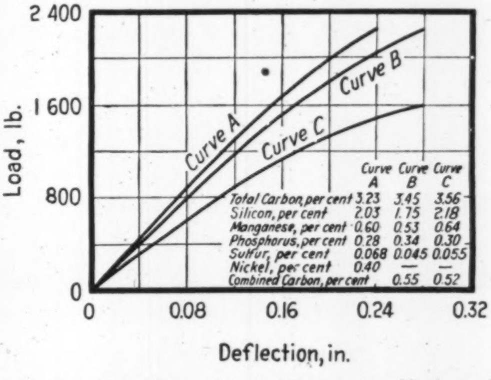


FIG. 2.—Tension Test Stress-Strain Curves of Two Metals at Room Temperature.



	Curve A	Curve B	Curve C
Total Carbon, per cent	3.23	3.45	3.56
Silicon, per cent	2.03	1.75	2.18
Manganese, per cent	0.60	0.53	0.64
Phosphorus, per cent	0.28	0.34	0.30
Sulfur, per cent	0.068	0.045	0.055
Nickel, per cent	0.40	—	—
Combined Carbon, per cent		0.55	0.52

FIG. 3.—Transverse Test Stress-Strain Curves for Various Cast Irons.
Specimens 1.2 in. in diameter, tested on 18-in. centers.

of steels, a major difference in the alloys being the presence of 8 to 10 per cent by volume of graphite in the gray iron. White iron consists largely of cementite plus pearlite, and mottled iron is made up of cementite, pearlite and graphite. The component, cementite, is hard and not easily distorted.

The stress-strain curve of an ordinary cast and annealed medium-carbon steel is shown in Fig. 1. As will be noted, at room temperature the stress-strain ratio is relatively constant up to a point (absolute proportionality of stress to strain over any stress range is questioned, and rightly so by investigators employing strainometers of extreme sensitivity). However, a stress-strain curve of the same steel at 1000° F. (540° C.) (Fig. 1) exhibits a quite different appearance.

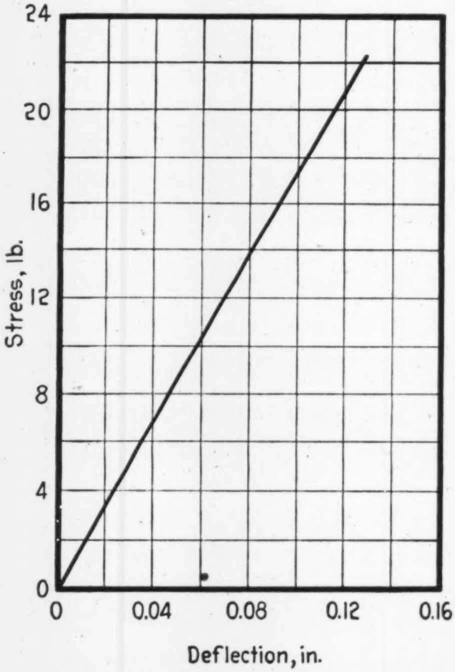


FIG. 4.—Transverse Test Stress-Strain Curve for Mottled Cast Iron.
Specimens 1.2 in. in diameter, tested on 18-in. centers.

The stress-strain diagram of any gray cast iron shows curvature almost from its inception (Fig. 2 shows tensile strength curves of two irons, one a high-test iron, iron B, the other a very low-strength iron, iron A, produced by pouring an iron adapted to light casting work into a heavy section). Figure 3 shows some characteristic transverse test stress-strain curves. The nature of the curves apparently suggests that gray irons are non-elastic (plastic) materials—which is rather contrary to everyday experience. The stress-strain curve of a mottled iron, shown in Fig. 4, exhibits apparent proportionality of stress to strain.

Steel within the proportional limit, as determined by room-temperature tests, exhibits elasticity. Careful tests by many investigators, including the author, indicate that well within the proportional limit there is no appreciable permanent deformation or set on repeated stressings. The observations merely confirm the conclusions based on the regular stress-strain-diagram characteristics. It is known, too, that the nature of the stress-strain diagrams of steel tested at elevated temperatures, say at 900° F. (480° C.) and above, indicates a tendency toward plasticity. As a matter of fact, under such conditions the material is known to creep or flow continuously at stresses below the proportional limit as usually determined. That is, under the conditions cited above where the stress-strain curve is straight the material can be considered elastic, within practical interpretation. The curvature of the diagram obtained at elevated temperatures suggests a higher order of plasticity, or a lower degree of elasticity. Above the equi-cohesive temperature the proportional limit as usually determined ceases to be a safe index of range of elasticity.

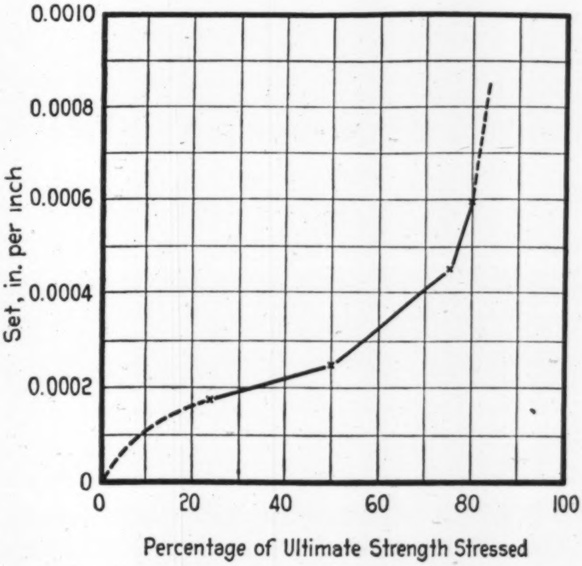


FIG. 5.—Permanent Set of Four Samples of an Iron.

However, Thum and Ude[1] have shown that if steels are drilled and the matrix continuity considerably broken up the character of the stress-strain diagram at room temperature is materially altered. The diagram is curved practically from inception resembling the curve typical of gray iron. Indeed Thum and Ude were attempting to simulate the probable effects of graphite flakes by artificially constructing the voids in the steel matrix.

Some experiments at the laboratories of the Lunkenheimer Co. indicate that the amount of "total" permanent set may not increase in direct proportion to the loading. As shown in Fig. 5, the ratio of set to stress increased as the stress was increased. The total sets were taken on four samples of the same iron, each stressed 50 times in tension and the loads varied from 25 per cent of ultimate strength on the first sample to 80 per cent on the fourth. Practically all the set for each loading was obtained on the first three to five stressings. As it is obvious that there would be no set at zero loading the author has ventured to project the curve from 25 per cent stress to zero stress.

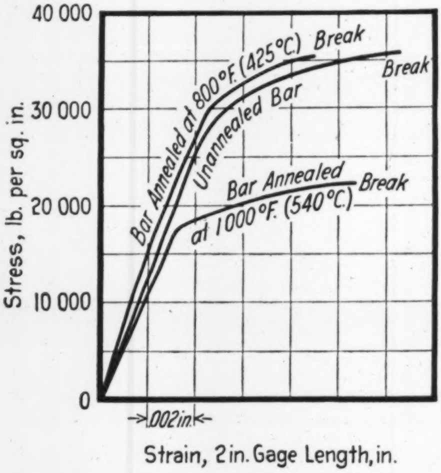


FIG. 6.—Stress-Strain Curves for Specimens of the Same Iron Prepared by Three Methods.

A number of repeated-stress tension tests have been run on various irons. In no case was there any apparent marked increase or decrease in tensile strength when the test specimen was finally broken after the stress cycles had been completed. However, there was a marked tendency for the re-stressed specimen, when finally loaded to rupture, to show more of a straight-line-with-elbow curve than a companion specimen which had not been subjected to cyclical stresses. Examples of this are shown in Fig. 6. In this case test specimens of the same iron were prepared as follows:

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[1] *Zeitschrift des Vereines Deutscher Ingenieure,* p. 251 (1930).

(*a*) As cast and machined.
(*b*) Annealed or normalized at 800° F. (425° C.) and machined.
(*c*) Annealed at 1600° F. (870° C.) and machined.

As shown in Fig. 6 all showed decided elbows on the final stress-strain curve carried to rupture of the bar. Other irons and other stresses showed the same effect but in every case the effect was more pronounced at the higher loadings (60 to 80 per cent). In the case of the 75-per-cent loading cyclical stresses with 50 repetitions of stress each on the irons shown in Fig. 6, the sharp elbows in the final stress-strain diagrams are just above this point, say at about 80 per cent of the ultimate strength, suggesting a possible "elastic limit" at this point.

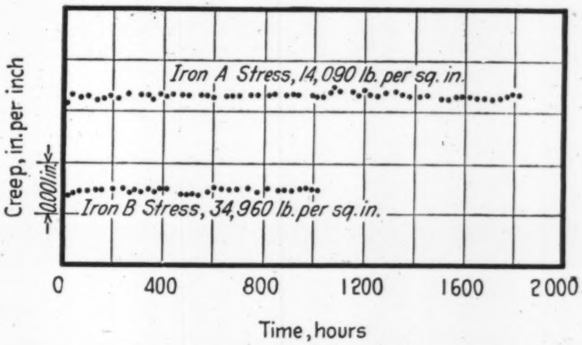

FIG. 7.—Creep Tests on Cast Iron at 100° F. (40° C.).

To test out the possibility of the actual existence of an elastic limit, creep tests were run on irons A and B referred to earlier in this paper (iron B, tensile strength 43,580 lb. per sq. in.; iron A, 17,610 lb. per sq. in.). The loads chosen were 34,960 lb. per sq. in. for iron B and 14,090 lb. per sq. in. for iron A, these loads being about 80 per cent of the ultimate tensile strengths of the respective samples. As shown by Fig. 7, after slight initial creep in the first 100 hours or less, no further creep was shown within the duration of the tests. (The initial readings were taken about 30 minutes after loading.) The following probably is the explanation of the straight-line-with-elbow type of curve mentioned above. Below the elbow the removal of permanent set naturally straightens out the curve. Above this point, set has not been removed and the curvature represents both permanent set and elastic deformation. This is illustrated diagrammatically in Fig. 8. According to the theory just given, the distance between the two curves at any point should equal x. This is the case at the three lower loadings, and there is a slight discrepancy at the highest loading for repeated stress. However this may be due to the two specimens not having been exactly the same strength originally. A number of samples have been examined carefully under the microscope and no evidence of incipient fractures was obtained.

The statement that the amount of permanent deformation or set is proportional to the amount of graphite is due to crushing of the graphite does not seem an adequate explanation of the set phenomena, although it probably is correct so far as it goes. Permanent deformation or set necessitates inelastic deformation of the continuous matrix, irrespective of the reaction or reactions of the non-continuous component. Let us for the moment assume that the non-continuous components (graphite flakes) consist of voids. Those familiar with the general distribution of graphite flakes in gray iron will at once perceive that since the distances between the voids are unequal, the stress distribution within the matrix will be far from uniform. This effect is illustrated diagrammatically in Fig. 9. Section A will be distorted severely and fail, even without permanent deformation in section B, if certain area ratios are maintained. The illustration of

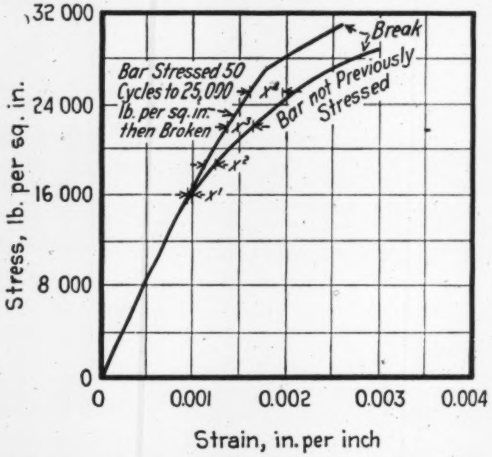

FIG. 8.—Stress-Strain Curves Illustrating the Theory of the "Straight-Line-with-Elbow" Type of Curve.

NOTE.—x represents the amount of actual permanent set after repeated stressing at loads shown. The distance x^4 is the permanent set of the bar whose final stress-strain curve is shown. x^1, x^2, and x^3 were determined on other bars, which were stressed to loads indicated.

course is extreme. However, in gray irons the paths of fracture are along the graphite flakes and through the matrix between flakes as shown in Figs. 10 and 11. The following tentative explanations of stress deformation relationships in gray iron are advanced:

1. The set phenomena are due to the overstressing of the portions of the matrix lying along paths of greatest stress intensity.

2. These paths of greatest stress intensity usually lie between those graphite flakes which most closely approach each other.

3. It is probable that overstressing various paths at a given loading results in readjustment of the matrix and the stiffening of such paths, accounting for the diminution and disappearance of further set on repeated re-stressing at constant maximum stress.

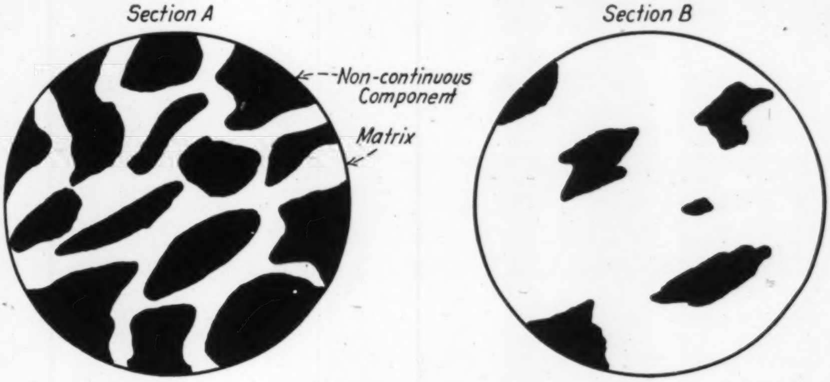

FIG. 9.—Diagrammatic Representations of Cross-Sections of an Imaginary Test Bar Possessing Great Variations in Structure in Different Parts of the Bar. This of course is an extreme or exaggerated illustration.

4. When the stress is increased the increase in set probably is due to:

(*a*) Further deformation of paths overstressed at lower loads, or
(*b*) Deformation along new paths whose limit of elastic deformation has been exceeded.

5. At lower deformations there probably is some compacting of graphite flakes by adjacent matrix. Beyond a certain limit of compaction the flakes cease to act as voids and offer resistance to compression. This possibly causes formation of more and more overstressed paths with increase in load, hence in certain ranges increase in amount of set is proportionately greater than increase in loading. It also is possible that discontinuous hard particles, such as certain steadite formations, have a somewhat similar effect. In case of white

and heavily mottled irons the hard component is practically continuous so that it itself carries most of the load, resulting in the type stress-strain diagram shown previously.

6. Obviously with more graphite present and unfavorable size and distribution of flakes, the stress gradients within the matrix (when the sample is loaded) are greater in number and intensity. Therefore resistance to permanent deformation varies inversely with the amount of graphite if size and distribution are constant. However the author has noted a number of cases where percentage of graphite and combined carbon were alike yet the "sets" were different. This also is true of tensile strength. One set of bars of different sizes, yet approximately constant in graphitic and combined carbon contents, showed that tensile strength and resistance to permanent deformation were lowered as section size increased. Therefore resistance to permanent deformation probably depends on amount, size and distribution of graphite and on the nature of the matrix rather than only on the amount of graphite present.

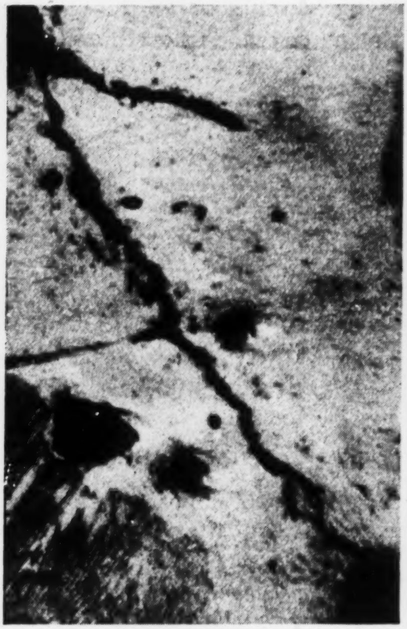

FIG. 10.—Gray Iron Etched in Picric Acid (× 2000).

Note crack proceeding between graphite flakes, tips of which are shown in diagonally opposite corners.

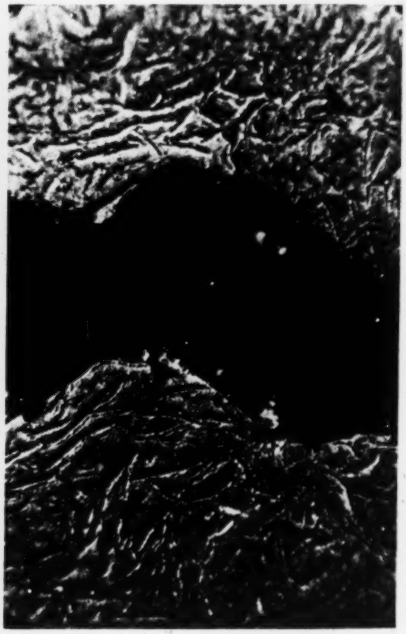

FIG. 11.—Gray Iron Unetched, Relief Polish, Silverman Illuminator (× 25).

The black line is a large crack. Note how rupture follows along flakes.

7. It has been stated that the tensile strength is not increased by the cold working involved in establishment of some permanent deformation. This appears to be true within the limits of experimental accuracy involved in the methods employed. The probable answer is that approximately the same amount of cold working is done whether the specimen be repeatedly stressed to a given load and broken or broken in a regular tension test. The difference in permanent deformation, while probably favoring the re-stressed material, is so slight that the ultimate effect of this difference or increase probably is negligible.

8. Gray irons have no true proportional limits. This is due to the extreme heterogeneity of the material and consequent stress gradients. There probably is no elastic limit (using the word in its usual sense) below the long-time ultimate strength. The long-time ultimate strength seems to be somewhat above 80 per cent of the ultimate tensile strength as determined by short-time test. Because of its heterogeneity actual general fracture in gray iron undoubtedly is preceded by many microscopic incipient fractures. This suggests that the long-time strength probably is somewhat below the strength determined on short-time test.

Acknowledgment.—The test results referred to in this paper were obtained, incidentally, in the course of certain other researches in the laboratories of the Lunkenheimer Co. The author is indebted to the Lunkenheimer Co. for permission to publish these results. The author is also indebted to Mr. H. Montgomery for the method of illustration employed in Fig. 8.

DISCUSSION

MR. A. H. DIERKER[1] (*presented in written form*).—Although agreeing with Mr. Bolton in most of his conclusions, we feel that a consideration of the permanent set phenomena in cast iron from a slightly different viewpoint may be of some interest. From photoelastic studies of materials as well as actual tests, it is known that high concentration of stress, in stressed materials, occurs adjacent to any discontinuities such as holes, cracks, etc. The concentration depends on the size and shape of the discontinuity, increasing with the size and sharpness of angle of any void. In other words we find a greater concentration next to a larger hole than a small one and a greater concentration at the end of a crack (provided it lies in a suitable plane) than adjacent to a round hole.

Malleable cast iron, although containing free graphite, has a quite definite modulus of elasticity and any appreciable permanent set does not occur below the elastic limit. We would conclude from this property that the graphite in malleable iron, due to its small size and rounded (nodular) form, has no serious effect on the physical properties of the material. In the case of gray cast iron, on the other hand, it would seem that the sharp angular discontinuities in the iron matrix caused by the presence of thin graphite flakes, would cause extremely high stress concentration adjacent to the edges of those flakes lying at the proper angle to the line of stress. This stress concentration can easily result in overstress of the affected parts which relieve themselves by permanent deformation or fracture. On the basis of this theory we would expect increasing stress concentration with a resultant greater permanent set at a given stress, with increasing size of graphite flakes. Conversely we would expect improved physical properties, under static loading, with decreasing size of graphite flakes or in any change of shape that would tend toward a more rounded form.

MR. J. W. BOLTON.[2]—We had considered adding another diagram to illustrate the variations in stress distribution attributable to variations in orientation of graphite flakes. A flake whose direction is parallel to the line of pull will have less effect on tensile strength than one lying normal to the axis of the test bar. May we not point out the well-known case of wrought iron as illustrating the point involved? Similarly rounded inclusions have less weakening effect than angular inclusions lying normal to the test bar axis. The stresses at the base of V notches always are high. Because of the presence of "structural V notches" (that is graphite flakes) cast iron is less affected by mechanically made notches than is steel, when under "fatigue" test.

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[2] Chief Chemist and Metallurgist, The Lunkenheimer Co., Cincinnati, Ohio.

Further explanation of Fig. 8 of the paper is in order. The permanent sets x^1, x^2 and x^3 shown on the diagram were determined on separate bars cyclically stressed to the loads shown. That is, there were five specimens of the same iron involved. The complete curves for the bar not cyclically stressed and the bar cyclically stressed to 25,000 lb. per sq. in. are shown, also the total permanent set of the latter bar (x^4), and the permanent sets only (x^1, x^2 and x^3) of three other bars cyclically stressed at loads 16,000, 18,000 and 22,000 lb. per sq. in., respectively.

We might mention that on a stress-strain curve carried to load and reversed to zero load the apparent initial permanent set (or set on first loading) will lessen somewhat if the test specimen is allowed to stand. That is, there is some elastic recovery. However, after a few restressings, this small elastic recovery is lost and the total permanent set is the same whether or not the cyclical stresses have had a time interval between cycles or been continued with no time interval.

MR. J. T. MACKENZIE.[1]—I do not think that Mr. Dierker's simple statement of the fact that malleable iron does not have any known plastic set would prove the case. I know in the case of the mottled cast iron, where you have very finely disseminated graphite, it takes very fine measurements to detect this permanent set, and I have not the slightest doubt but that malleable iron will show some permanent set. It is well known in the testing of steel that if you want to get a beautiful straight-line performance for a class of students you have to go around the afternoon before and give it at least one loading.

The work of Thum and Ude showed the very thing that Mr. Dierker is talking about. The difference in the round holes and saw slits did make quite a difference, and, of course, we know that the properties of the steel that these Germans tested was not changed by the fact that they drilled holes and sawed slits in it.

MR. H. BORNSTEIN.[2]—Mr. Bolton has given us a very logical explanation of the mechanism of deformation in cast iron. We are getting new ideas in respect to physical properties of cast iron. We used to think entirely in terms of transverse and tension tests. It is only recently that we have considered fatigue and creep properties. I think it is worth while to know that the creep value of cast iron is at least 80 per cent of the tensile strength. It makes cast iron a valuable material for that type of service.

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[1] Chief Chemist, American Cast Iron Pipe Co., Birmingham, Ala.

[2] Director of Laboratories, Deere and Co., Moline, Ill.

MR. J. E. HURST[1] (*by letter*).—I believe the mechanism of deformations in gray iron must take into consideration many other factors in addition to permanent set. A permanent set test on initial loading is a regular routine test with us in our laboratory, and we have been for many years able to study the behavior of cast iron from this point of view. Our experience does not enable us to agree with the statement made by Mr. Bolton that "the set usually increases with increase in size of section, or inversely as the tensile strength." The results of a comprehensive investigation, by the writer, of the mechanical properties of a variety of pig irons all cast in exactly the same manner under carefully controlled conditions, are not quite in accordance with this statement.[2]

I am in complete agreement with Mr. Bolton that the hypothesis advanced by Mr. J. T. MacKenzie that a large part of the set is due to the crushing of graphite flakes is quite untenable. It appears to be evident from our investigations here that the character of the matrix has a good deal of influence on the permanent set phenomena. The permanent set determinations on a series of irons before and after subjection to oil hardening and tempering treatment indicate that the permanent set is considerably reduced by oil hardening and tempering, and there does appear in some cases to be a tendency to recover a permanent set after tempering in the higher ranges of temperature. This would appear to confirm that the permanent set phenomena have some relation to the character of the matrix.

Mr. Bolton appears to have completely neglected the influence of internal stress on the permanent set. Our investigations here lead us to the view that the influence of internal stress cannot by any means be neglected.

Another aspect of Mr. Bolton's paper which calls for comment is the view taken with regard to the limits of proportionality in cast iron. It is of course quite true that the sensitivity of the measurements of strain influences our conception of the limit of proportionality. We find in our experiments, particularly with our centrifugally cast material, many examples where the stress-strain curves show the initial portions very closely approximating conditions of true proportionality, and showing distinct evidence of limits of proportionality.

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[1] Technical Director, Sheepbridge Stokes Centrifugal Castings Co., Ltd., Chesterfield, England

[2] *Proceedings*, Manchester Assn. Engrs. (1931-1932).

MR. BOLTON (*author's closure by letter*).—Referring to Mr. Hurst's criticism of the statement that "the set usually increases with increase in size of section, or inversely as the tensile strength," we found this to be so on the samples we tested, and MacKenzie confirms our contention that set usually varies inversely as strength.

Theoretically the influence of internal stress should not be neglected, but we had no good way of evaluating it. This factor affects a tension test less than it does a transverse test. We should like to point out that we did not take the thermal effects into consideration, we did not offer an adequate explanation for hysteresis loop, and that the possibility of elastic recovery with time, on a given cycle, was neglected. Possibly these points will be considered in further researches.

We should like to have Mr. Hurst furnish more data, and examples of gray irons, as cast, showing any real proportional limits. Some irons may show apparent proportionality of strain to stress over short ranges, but I doubt that this proportionality will seem so evident if sufficiently sensitive extensometric equipment is employed.

INFLUENCE OF RECRYSTALLIZATION TEMPERATURE AND GRAIN SIZE ON THE CREEP CHARACTERISTICS OF NON-FERROUS ALLOYS

By C. L. Clark[1] and A. E. White[2]

Synopsis

This paper presents the results of long-time creep tests conducted on non-ferrous alloys of the copper-zinc and copper-zinc-tin series, at temperatures both above and below their lowest recrystallization temperature. Certain of the materials investigated were of identical chemical composition, but varied in grain size.

The results presented indicate the creep characteristics to be greatly influenced by the recrystallization temperature and by the grain size. It is shown that not only is there a sharp decrease in a metal's ability to resist creep as the recrystallization temperature is passed, but also there is a change in the nature of the creep characteristics. At temperatures below this temperature, metals are able to resist stresses of appreciable magnitude without measurable continuous creep, while at temperatures above, appreciable continuous creep occurs under the stresses used with a probability that continuous creep would occur at any stress.

Grain size and recrystallization temperature have been found to be so related that at temperatures below the lowest recrystallization temperature, fine-grained materials offer the greater creep resistance, while at temperatures above, the coarse-grained material is superior. These findings support the hypotheses previously advanced by the authors[3] regarding the effect of grain size on a metal's high-temperature stability.

Introduction

During the past several years considerable time and effort have been expended by many investigators, both in this country and abroad, in the determination of the creep characteristics of many metals and alloys at elevated temperatures. A large share of this work, however, has consisted mainly in the procurement of numerical creep data on many metallic materials at various temperatures. While a great need still exists for additional information of this type, it is felt that more attention should now be given to the various factors which influence the creep or flow of metals and alloys at the higher temperatures. This is especially necessary if the demands of industry are to be met for alloys of superior creep resistance at ever increasing temperatures. It is true that alloys have already been developed which show promise of outstanding creep resistance, but the majority of these have been produced by more or less haphazard methods. Before alloys can be developed for this purpose on a truly scientific basis, more will have to be known of the influence of the various factors which affect or influence creep.

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[1] Research Engineer (Metallurgy), Department of Engineering Research, University of Michigan, Ann Arbor, Mich.

[2] Professor of Metallurgical Engineering, and Director of Department of Engineering Research, University of Michigan, Ann Arbor, Mich.

[3] C. L. Clark and A. E. White, "The Stability of Metals at Elevated Temperatures," *Engineering Research Bulletin, No. 11*, Department of Engineering Research, University of Michigan, November, 1928, p. 68.

While there are a large number of factors which may influence the actual or observed creep characteristics of metallic materials, those which are believed to be of the greatest importance are: Chemical composition, heat treatment, recrystallization temperature, grain size, method of manufacture, and testing procedure. Many of these factors are overlapping and it is difficult to consider one without one or more of the others. Especially is this true of the recrystallization temperature and chemical composition, and, to a somewhat lesser extent, of grain size and heat treatment.

During the course of a general investigation as to creep characteristics of a number of selected non-ferrous alloys, data were obtained bearing upon the effects of recrystallization temperature and grain size. This paper is accordingly presented for the purpose of setting forth the findings which show the influence of these two factors.

INFLUENCE OF RECRYSTALLIZATION TEMPERATURE

The authors are of the opinion that the recrystallization temperature of a metal is one of the outstanding factors in determining a metal's creep characteristics. All metallurgists realize that every metal has a recrystallization temperature and that usually the recrystallization temperature of a given metal is different from that of any other metal. Also, in the same metal, the recrystallization temperature is affected by a large number of factors, among which may be mentioned: the amount of deformation, the size of the grains prior to deformation, the purity of the metal, the temperature at which the deformation was effected, and the length of time at heat.

From the above factors producing a variation in temperature, it is readily appreciated that an expression such as "recrystallization temperature" does not in itself make possible one single temperature for any one metal. As a matter of fact, it may be better to think of the recrystallization temperature as a temperature range, rather than as a single temperature. In this paper the term will be used to designate the lowest recrystallization temperature, which has been designated by Jeffries and Archer as the equi-cohesive temperature.

Many claim that a metal's ability to recrystallize is merely a function of time and, provided sufficient time is allowed, complete recrystallization will occur at any temperature. Whether or not this claim is correct, any statements the authors may make will apply, even under this hypothesis, by inserting the word "apparent" before "lowest recrystallization temperature."

Materials Employed:

Several non-ferrous alloys were employed for this study, the compositions of which are given in Table I. The alloys belong either to the copper-zinc or to the copper-zinc-tin series. In the copper-zinc alloys, the amount of copper varied from 85.00 to 60.21 per cent, while in the copper-zinc-tin alloys, the amount of this element varied from 77.26 to 58.79 per cent. All of these materials except two were examined in the hot-rolled condition. The two exceptions were the 70-30 brass and the 70-29-1 admiralty metal, both of which were given a final cold draw of $\frac{1}{8}$ in. on a final diameter of $\frac{3}{4}$ in. The materials were all secured from commercial firms, the sources being given in Table I.

TABLE I.—CHEMICAL COMPOSITION, MECHANICAL CONDITION, AND COMMERCIAL SOURCE OF NON-FERROUS ALLOYS.

Designation	Type of Material	Chemical Composition, per cent			Condition	Source
		Copper	Zinc	Tin		
A	Admiralty	71.05	27.95	0.97	Final $\frac{1}{8}$ in. cold draw	American Brass Co.
B	Brass	70.48	30.44	....	Final $\frac{1}{8}$ in. cold draw	American Brass Co.
E-1	Brass	60.21	39.72	0.16	0.020 mm. grain size	Bridgeport Brass Co.
R-85	Brass	85.00	14.92	....	0.030 mm. grain size	Bridgeport Brass Co.
E-2	Admiralty	77.26	21.61	1.18	0.020 mm. grain size	Bridgeport Brass Co.
E-3	Tobin bronze	58.79	40.43	0.88	0.025 mm. grain size	Bridgeport Brass Co.

Procedure:

The experimental work consisted in determining the lowest temperature of recrystallization and in conducting long-time creep tests at temperatures both above and below the lowest recrystallization temperature. The short-time tensile properties of these materials were also determined at elevated temperatures, but these results, as well as certain of the creep results, have already been presented.[1]

For the determination of the lowest temperature of recrystallization, specimens of each alloy were severely cold worked, after which they were subjected to tempering at various temperatures. They were maintained at temperature for 100 hours, hardness readings being taken at room temperature before and after the heating operation. The temperature at which a sharp decrease in hardness was obtained was designated as the lowest recrystallization temperature. The location of this temperature was also checked by metallographic means. The apparatus used in the long-time creep tests has already been described in the literature.[1] The procedure consists in applying a fixed load and maintaining it constant until either the flow comes to a complete stop, at least within the sensitivity of the apparatus, or until it has assumed a steady rate for at least 200 hours. The load is then increased and the process repeated until at least four rates of creep have been obtained.

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[1] C. L. Clark and A. E. White, "Properties of Non-Ferrous Alloys at Elevated Temperatures," Fuels and Steam Power, *Transactions*, Am. Soc. Mechanical Engrs., Vol. 53, No. 8, p. 183 (1931).

TABLE II.—EFFECT OF INCREASING DRAWING TEMPERATURES ON THE HARDNESS OF SEVERELY COLD-WORKED NON-FERROUS ALLOYS OF THE COPPER-ZINC, COPPER-ZINC-TIN SERIES.

DESIGNATION	ALLOY	ROCKWELL HARDNESS, "B" SCALE, AFTER HEATING AT DESIGNATED DRAWING TEMPERATURES					
		70° F. (21° C.)	200° F. (95° C.)	300° F. (150° C.)	400° F. (205° C.)	500° F. (260° C.)	600° F. (315° C.)
R-85....	85–15....	79	77	76.5	74.0	72	50
E-2.....	77–22–1..	85	85	82	85	82	72
E-1.....	60–40....	82	81	82	75	70	59
E-3.....	59–40–1..	88	85	84	79	75	70
B.......	70–30....	89	96	98	98	67	..
A.......	70-29-1..	95	96	100	101	72	..

TABLE III.—TEMPERATURE OF RECRYSTALLIZATION OF NON-FERROUS ALLOYS OF THE COPPER-ZINC AND COPPER-ZINC-TIN SERIES.

Designation	Alloy	Recrystallization Temperature	
		Computed from Hardness Tests	Computed from Metallographic Examination
R-85.....	85–15	Over 500° F. (260° C.), under 600° F. (315° C.)	Over 500° F. (260° C.), under 600° F. (315° C.)
E-2......	77–21–1	Over 500° F. (260° C.), under 600° F. (315° C.)	Over 500° F. (260° C.), under 600° F. (315° C.)
E-1......	60–40	Over 300° F. (150° C.), under 400° F. (205° C.)	Over 300° F. (150° C.), under 400° F. (205° C.)
E-3......	59–40–1	Over 300° F. (150° C.), under 400° F. (205° C.)	Over 300° F. (150° C.), under 400° F. (205° C.)
B........	70–30	Over 400° F. (205° C.), under 500° F. (260° C.)	Over 400° F. (205° C.), under 500° F. (260° C.)
A........	70-29-1	Over 400° F. (205° C.), under 500° F. (260° C.)	Over 400° F. (205° C.), under 500° F. (260° C.)

It is realized that the creep characteristics as determined by this so-called up-step method of loading may be different, at least at certain temperatures, than those determined by either the single-step or down-step method of applying the load. All the results herein considered, however, were obtained by the up-step method, and the question of the relative magnitude of values obtained by these three methods is reserved for a later paper.

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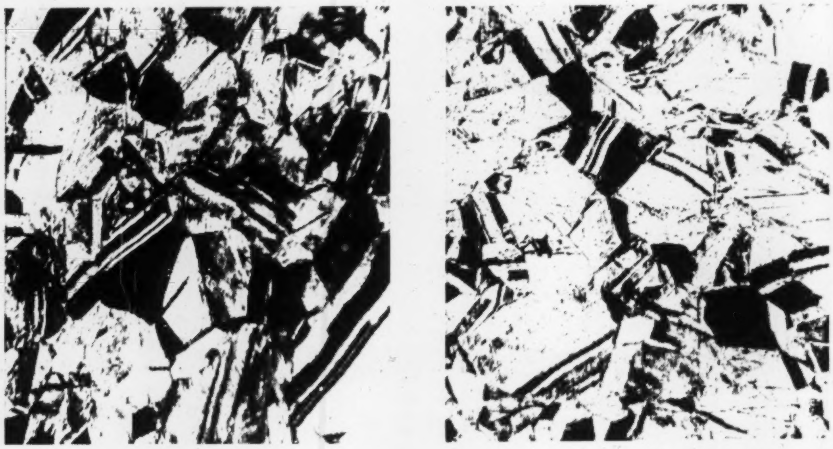
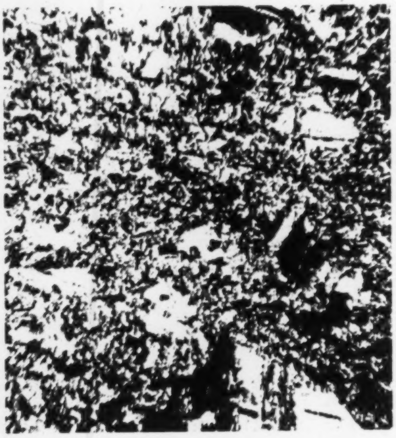
[1] A. E. White, C. L. Clark, and L. Thomassen, "An Apparatus for the Determination of Creep at Elevated Temperatures," Fuels and Steam Power, *Transactions*, Am. Soc. Mechanical Engrs., Vol. 52, No. 27, p. 347 (1931).



(*a*) Severely cold-worked.

(*b*) Severely cold-worked. Drawn 100 hours at 500° F. (260° C.). No recrystallization.



(*c*) Severely cold-worked. Drawn 100 hours at 600° F. (315° C.). Recrystallization.

FIG. 1.—Photomicrographs of 77–22–1 Alloy (×75).

Lowest Recrystallization Temperature:

The results of the tests to determine the recrystallization temperature are given in Tables II and III, and typical photomicrographs showing the effect of annealing at 500 and 600° F. (260 and 315° C.) for 100 hours on the structure of cold-worked 77 per cent copper, 22 per cent zinc, 1 per cent tin alloy are given in Fig. 1. The alloys considered fall into two groups. Those containing 70 per cent or more of copper have a range above 400 and under 600° F. (205 and 315° C.), while those containing 60 per cent of copper or less have a range between 300 and 400° F. (150 and 205° C.).

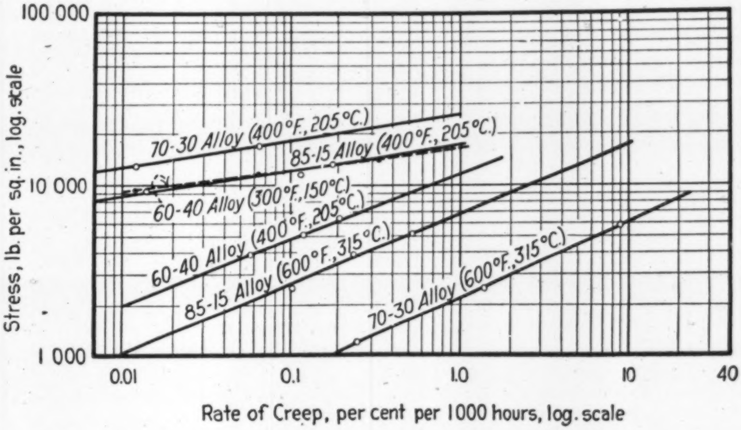


FIG. 2.—Creep-Stress Curves for Copper-Zinc Alloys.

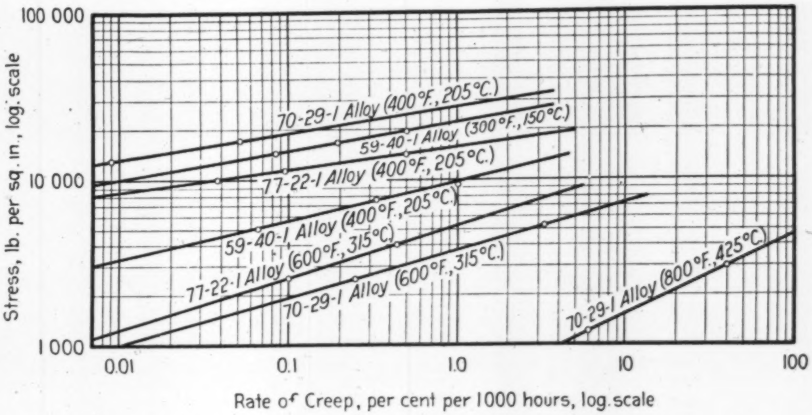
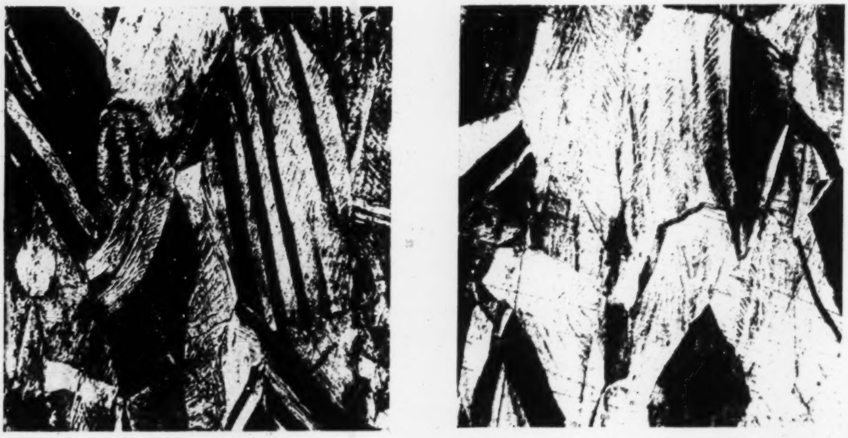


FIG. 3.—Creep-Stress Curves for Copper-Zinc-Tin Alloys.

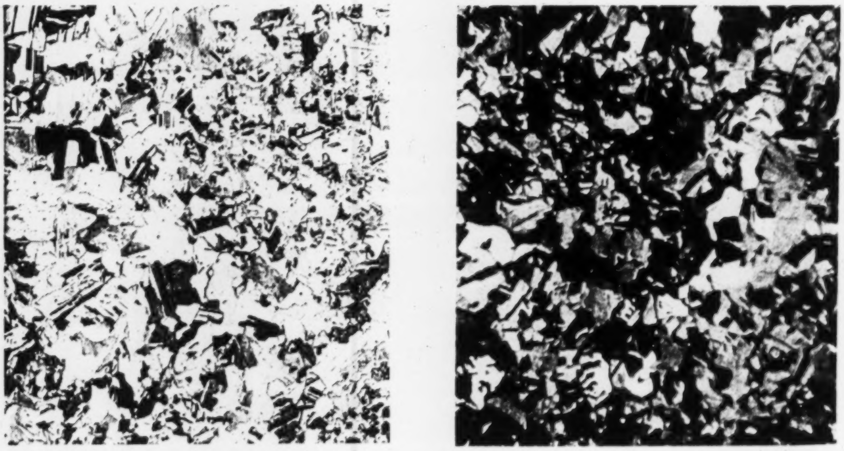
Creep Results:

The results of the long-time creep tests are given in Figs. 2 and 3. Rather than include the large number of time-elongation curves which have been obtained as a result of the creep tests, the method shown in the figures has been resorted to. This method is based on previous work which has shown that, if the logarithm of the rate of creep be plotted against the logarithm of the stress producing that deformation, a straight-line relationship results, at least under certain conditions. This method allows a large number of results to be presented in a condensed form. It also simplifies the interpretation of the findings. For example, either the rate of deformation corresponding to a given stress or the stress corresponding to a given rate of deformation may be readily determined.



(*a*) As-received condition.

(*b*) Creep specimen at 400° F. (205° C.). Tested for 2000 hours.



(*c*) Creep specimen at 600° F. (315° C.). Tested for 1600 hours.

(*d*) Creep specimen at 800° F. (425° C.). Tested for 500 hours.

FIG. 4.—Photomicrographs of 70–30 Alloy (× 75).

Figure 2 gives the results of the creep tests on the copper-zinc alloys using logarithmic plotting. It will be observed that the points in all cases fall on practically straight lines and that these lines may be classified into two groups with all the lines in any one group approximately parallel to each other. The 70-30 and 85-15 brass at 400° F. (205° C.) and the 60-40 brass at 300° F. (150° C.) fall into one group, while the other is composed of the 70-30 and 85-15 brass at 600° F. (315° C.) and the 60-40 brass at 400° F. (205° C.). Referring to Table III, it is seen that the lines with the smaller slope represent results obtained at temperatures below the lowest recrystallization temperature, while the lines with the greater slope were obtained at temperatures above the lowest recrystallization temperature.

TABLE IV.—INFLUENCE OF RECRYSTALLIZATION TEMPERATURE RANGE ON SLOPE RESULTING FROM PLOTTING LOGARITHM OF STRESS AGAINST LOGARITHM OF RATE OF CREEP.

Alloy	Recrystallization Temperature Range		Creep Test Temperature		Position with Respect to Recrystallization Temperature	Angle of Slope, deg.
	deg. Fahr.	deg. Cent.	deg. Fahr.	deg. Cent.		
59-40-1	300 to 400	150 to 205	300	150	below	9.5
59-40-1	300 to 400	150 to 205	400	205	above	13.5
60-40	300 to 400	150 to 205	300	150	below	7.5
60-40	300 to 400	150 to 205	400	205	above	21.5
70-30	400 to 500	205 to 260	400	205	below	9.0
70-30	400 to 500	205 to 260	600	315	above	24.0
70-29-1	400 to 500	205 to 260	400	205	below	9.0
70-29-1	400 to 500	205 to 260	600	315	above	16.5
70-29-1	400 to 500	205 to 260	800	425	above	26.0
77-22-1	500 to 600	260 to 315	400	205	below	8.0
77-22-1	500 to 600	260 to 315	600	315	above	17.5
85-15	500 to 600	260 to 315	400	205	below	9.0
85-15	500 to 600	260 to 315	600	315	above	22.0

In order to verify these findings, specimens of the 70-30 brass were subjected to metallographic examination in the "as received" condition and after having been subjected to the creep tests at 400, 600, and 800° F. (205, 315 and 425° C.). The results are shown in Fig. 4. From this it is evident that no apparent structural change has occurred during the creep test at 400° F. (205° C.), even though this test lasted for over 2000 hours, while at 600° F. (315° C.) considerable recrystallization has occurred, and at 800° F. (425° C.) the recrystallization was not only complete but some grain growth had occurred.

Figure 3 gives the corresponding creep test results on the copper-zinc-tin alloys. Again the points fall on approximately straight lines, and the lines may be divided into two groups depending on their slope. The lines with the least slope give the results from the 70-29-1 and 77-22-1 alloys at 400° F. (205° C.) and of the 59-40-1 alloy at 300° F. (150° C.), while the lines with the greater slope express the results obtained from the 70-29-1 alloy at 600 and 800° F. (315 and 425° C.), the 77-22-1 alloy at 600° F. (315° C.), and the 59-40-1 alloy at 400° F. (205° C.). From Table III, it is seen that, as before, this division is closely connected with the recrystallization temperature.

The data given in Figs. 2 and 3 are presented in Table IV. Attention is directed to the sharp change in the slope of the line expressing the logarithmic relationship between the stress and the rate of creep produced by that stress as the recrystallization temperature is passed. Above this temperature range, the slope of the line is very much greater than it is below this temperature range.

The authors are aware of a statement previously made to the effect that logarithmic plotting, of the type herein used, produced parallel lines for a large number of materials over a wide range of temperatures. The results now given appear to indicate that such may not always be the case, and it is believed the above statement was based largely on results from materials which were all tested either above or below their lowest recrystallization temperature. In fact, the results included lend further support to this latter supposition, for the logarithmic lines expressing the results from all the materials, that is, the copper-zinc, and the copper-zinc-tin alloys, at temperatures below their lowest recrystallization temperature, were approximately parallel. For temperatures above the lowest recrystallization temperature, a similar parallelism does not exist with the different materials. While the lines for the copper-zinc alloys are approximately parallel, those for certain of the copper-zinc-tin alloys have a decidedly smaller slope. This may be accounted for by the fact that the temperatures at which these latter alloys were tested were not so far above the lowest recrystallization temperature as was true for the other two classes of materials.

Again, were the creep-stress lines for the metals herein considered which were tested at temperatures above the equi-cohesive temperature extrapolated to any considerable amount they would cross the extrapolated creep-stress lines for the same metals when tested at temperatures below the equi-cohesive temperature. This would produce an apparent paradox in that it would reverse all of the present-day accepted metallurgical facts to the effect that, for a given metal under a given stress, the rate of creep is the higher the higher the temperature. One, however, is not justified in extrapolating too far, for two radically different types of phenomena are taking place.

In the case of the alloys tested above the equi-cohesive temperature, flow taking place in the metal is largely plastic in character. In time, therefore, the creep-stress line would flatten out because of the reduction of cross-section of the metal and approach one of the stress lines as an asymptote. In the case of the alloys tested below the equi-cohesive temperature, much elastic, as well as possibly some plastic, deformation is occurring. This elastic deformation results in the strain hardening of the metal. This in time would tend to decrease the rate of creep. The slopes of the creep-stress lines, therefore, would not tend to become less until a marked reduction of area had occurred.

TABLE V.—LONG-TIME CREEP CHARACTERISTICS OF NON-FERROUS ALLOYS AT ELEVATED TEMPERATURES.

Material	Temperature of Recrystallization	Temperature		Proportional Limit, lb. per sq. in.	Stress to Produce Designated Rate of Creep, lb. per sq. in.			
		deg. Fahr.	deg. Cent.		No Measurable Flow	Rate of Creep, 0.01 per cent flow per 1000 hours	Rate of Creep, 0.10 per cent flow per 1000 hours	Rate of Creep, 1.00 per cent flow per 1000 hours
70-30....	Over 400° F. (205° C.)	400	205	13 000	10 000	12 700	18 000	27 000
	Under 500° F. (260° C.)	600	315	6 750	[a]	290	850	2 150
		800	425	4 000	[a]	[a]	[a]	[a]
70-29-1..	Over 400° F. (205° C.)	400	205	21 000	10 000	13 000	19 000	27 000
	Under 500° F. (260° C.)	600	315	15 000	[a]	1 000	1 950	3 800
		800	425	8 000	[a]	54	160	500
85-15....	Over 500° F. (260° C.)	400	205	7 000	7 500	8 800	12 000	17 000
	Under 600° F. (315° C.)	600	315	5 500	[a]	1 000	2 600	6 800
60-40....	Over 300° F. (150° C.)	300	150	7 500	7 500	9 000	12 000	17 000
	Under 400° F. (205° C.)	400	205	5 000	[a]	2 000	4 750	11 500
77-22-1..	Over 500° F. (260° C.)	400	205	8 000	7 500	10 500	13 000	16 500
	Under 600° F. (315° C.)	600	315	4 000	[a]	1 200	2 500	5 300
59 40-1.	Over 300° F. (150° C.)	300	150	14 000	10 000	12 000	15 000	21 500
	Under 400° F. (205° C.)	400	205	6 000	[a]	3 500	5 700	9 400

[a] Known to be very small and believed to approach zero.

In no case would it seem advisable to extrapolate to a value in which the rate of creep for 1000 hours exceeded 10 per cent, because by so doing the amount of reduction which the metals would suffer would be sufficient to change the conditions. Up to some such value, however, the data presented and the resultant findings seemed apparently to hold.

Another change, in addition to the change of slope of the logarithmic lines, occurs as the lowest recrystallization temperature is passed, that is, a change in the creep characteristics themselves.

The authors have always believed that as long as a metal was subjected to stresses below a certain fixed maximum at temperatures below their lowest recrystallization temperature, sufficient strain hardening would occur to stop any measurable creep, or continuous deformation, and, likewise, if the temperature considered was above the lowest recrystallization temperature, then continuous measurable deformation would occur under practically any stress, regardless of its magnitude.

The results obtained support this hypothesis. Referring to Table V, it is seen that with the 70-30, 70-29-1, 85-15, and the 77-22-1 alloys appreciable stresses were withstood at 400° F. (205° C.) with no continuous measurable flow, at least within the sensitivity of the apparatus employed, while at 600° F. (315° C.), continuous flow was obtained with each of these alloys with the smallest stresses employed.

Likewise, with the 60-40 and the 59-40-1 alloys continuous measurable flow was not obtained at 300° F. (150° C.) with certain of the stresses used, but was obtained in all cases for all of the stresses used at 400° F. (205° C.). If the limiting temperatures for each alloy, below which a definite stress is required to produce continuous creep and above which continuous creep is obtained with the smallest stresses employed, be compared with the respective lowest recrystallization temperatures as given in Table III, good agreement will be seen to exist.

These results, therefore, do lend support to the hypothesis that continuous flow occurs under any stress whatsoever at temperatures above the lowest recrystallization temperature, while at those below, stresses of definite magnitude are required to produce continuous measurable creep.

Some may question whether flow actually comes to a stop or whether it is occurring at such a small rate that the measuring apparatus is not sufficiently sensitive to detect it. Such a question is, of course, difficult, if not impossible, to answer. Our present measuring system is sensitive to 0.0000028 in., and even if it were capable of reading to one-hundredth or even one-thousandth of this value, a similar question could still be raised. On the basis of the results obtained, and from theoretical considerations, however, it is felt that the above conclusions regarding the influence of the lowest recrystallization temperature on creep characteristics are valid.

It is interesting to consider further the stress necessary to produce continuous deformation at temperatures just below the lowest recrystallization temperature. Again, referring to Table V, it is observed that in every case except one this stress is related to the carefully determined proportional-limit value at the corresponding temperature. The one exception is the cold-worked 70-29-1 alloy. With this latter alloy the proportional-limit value is considerably above the apparent limiting creep value. This is probably due to the proportional-limit value having been increased by the cold-working to which this material was initially subjected. It, therefore, appears that at temperatures just below the recrystallization temperature, carefully determined proportional-limit values may be a measure of a metal's resistance to continuous creep, if it is not in a cold-worked condition.

GRAIN SIZE

Many conflicting statements have been made regarding the effect of grain size upon a metal's high-temperature strength characteristics, and very few experimental data have been offered to support these statements. Purely from a theoretical viewpoint, grain size should play an important part in a metal's creep characteristics. It is well known that at room temperature, fracture resulting from tension, and thus the greatest share of deformation, occurs through the grains.[1] In other words, at these temperatures the material surrounding the grains, or the grain boundaries, is stronger and more able to withstand deformation than the grains themselves, and therefore, a fine-grained material will possess the greater strength because of the greater relative amount of grain boundaries present.

TABLE VI.—CHEMICAL COMPOSITION OF NON-FERROUS ALLOYS WITH VARYING GRAIN SIZE.

		Chemical Composition, per cent			
Designation	Alloy	Copper	Zinc	Tin	Grain Size, mm.
E-2	77-22-1	77.26	21.61	1.18	0.020
E-20	77-22-1	77.24	21.77	1.02	0.045
E-3	59-40-1	58.79	40.43	0.88	0.025
E-24	59-40-1	60.08	38.72	0.83	0.045

As the temperature is increased, however, the material surrounding the grains, or the grain boundaries, weakens at a more rapid rate than the crystals, and a temperature is soon reached at which fracture proceeds around, rather than through, the grains.[2] At this temperature, a coarse-grained material will possess the greatest strength because of the presence of a larger amount of the stronger phase, the crystalline. There is still considerable question as to the location of this apparently critical temperature. The authors believe that this temperature is the lowest recrystallization temperature, or the equi-cohesive temperature. They also advance the suggestion that the following two conditions exist, depending on what temperatures are under consideration.

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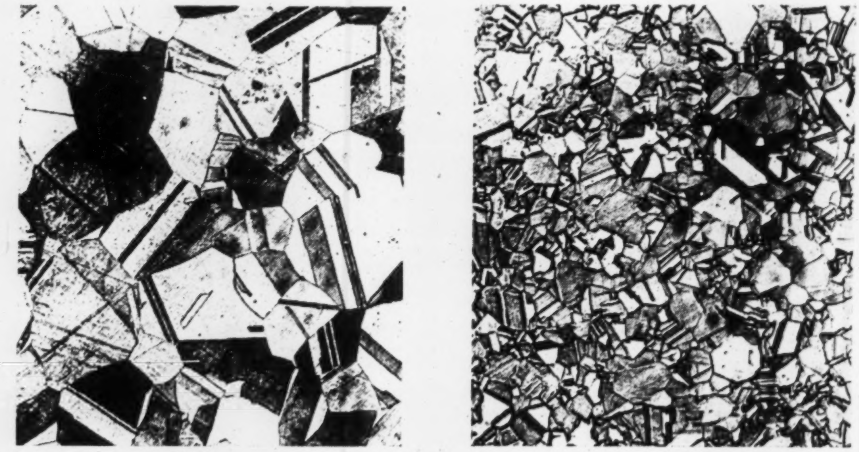
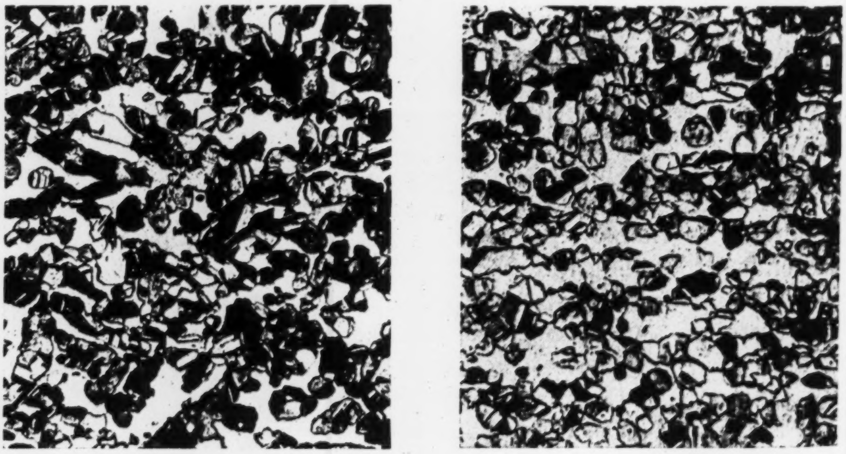
[1] A. E. White and R. Schneidewind, "Fractures in Boiler Metal," Fuels and Steam Power, *Transactions*, Am. Soc. Mechanical Engrs., Vol. 53, No. 8, *p*. 193 (1931).

[2] W. Rosenhain, "The Plastic Deformation and Fracture of Metals," *The Engineer*, October 14, 1927, p. 422.



(a) As-received condition, coarse grained. (b) As-received condition, fine grained.

FIG. 5.—Photomicrographs of 77–22-1 Alloy (× 75).



(a) As-received condition, coarse grained. (b) As-received condition, fine grained.

FIG. 6.—Photomicrographs of 59–40–1 Alloy (× 75).

1. At temperatures below the lowest recrystallization temperature, a fine-grained material possesses the greater creep resistance; and

2. At temperatures above the lowest recrystallization temperature, a coarse-grained material possesses the greater creep resistance.

Materials and Procedure:

Two non-ferrous alloys of the copper-zinc-tin series, each of which had been treated to produce two different grain sizes, were used for this investigation. Their chemical composition and grain size are given in Table VI. Their metallographic structures are also shown in Figs. 5 and 6. The non-ferrous alloys were used because of the ease with which it was possible to obtain a relatively great variation in grain size. The results obtained, however, are believed to be applicable to any metal or alloy.

The tests conducted on these materials were long-time creep tests at temperatures both below and above their lowest recrystallization temperature. The procedure used in these tests is the same as that mentioned previously in this paper.

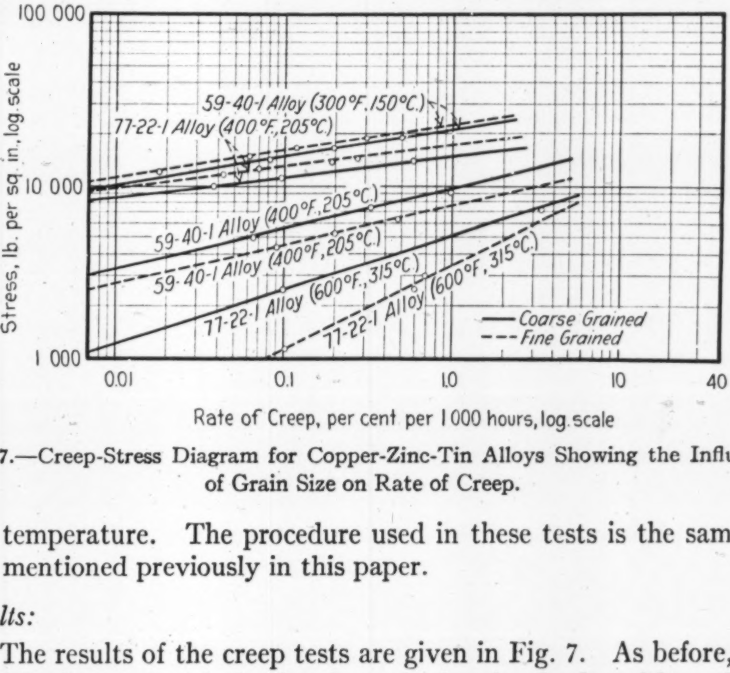


FIG. 7.—Creep-Stress Diagram for Copper-Zinc-Tin Alloys Showing the Influence of Grain Size on Rate of Creep.

Results:

The results of the creep tests are given in Fig. 7. As before, the logarithmic system of plotting is used, that is, the logarithm of the rate of creep is plotted against the stress producing it. At 400° F. (205° C.), the fine-grained 77-22-1 alloy is more resistant to continuous creep than the coarse-grained material, and at 600° F. (315° C.), the coarse-grained alloy offers the greater resistance. Since the lowest temperature of recrystallization of this material has been found to be between 500 and 600° F. (260 and 315° C.), Table III, the hypothesis just advanced appears to be supported. Likewise. with the 59-40-1 alloy, the fine-grained material is the more resistant at 300° F. (150° C.), while the coarse-grained material is superior at

400° F. (205° C.). Again, from Table III, this change is closely related to the lowest recrystallization temperature.

On the basis of the results obtained from both of these alloys, it may be said that at temperatures below the lowest recrystallization temperature, fine-grained materials possess the greater creep resistance, while at temperatures above, the coarse-grained material has the greater resistance to creep.

CONCLUSIONS

Creep tests conducted on alloys of the copper-zinc and copper-zinc-tin series at temperatures both above and below their lowest recrystallization temperature, and in certain cases in which a considerable variation in grain size existed, allow the following general conclusions:

1. At temperatures below the lowest recrystallization temperature, the alloys tested were capable of withstanding stresses of appreciable magnitude without continuous deformation or creep, at least within the sensitivity of the apparatus employed, and for those temperatures in the immediate neighborhood of the lowest temperature of recrystallization, the limiting stress below which continuous creep is not obtained, may, in the case of the alloys which have a stable structure under the given testing conditions, be the carefully determined proportional-limit value at the corresponding temperature.
2. At temperatures above the lowest recrystallization temperature, continuous creep was obtained with the lowest stresses employed and it is believed that such would also be the case at any stress.
3. At temperatures below the lowest recrystallization temperature, the fine-grained materials examined possessed the greater creep resistance, while at temperatures above the recrystallization temperature, the coarse-grained materials offered the greater resistance to creep.
4. A change in the slope of the lines, resulting from the logarithmic plotting of stress *versus* rate of creep produced by that stress, appears to occur as the lowest temperature of recrystallization is passed. For the metals tested all the lines expressing results obtained below this temperature are approximately parallel, but their slope is not as great as that of the lines obtained above the lowest recrystallization temperature. At temperatures above this apparently critical temperature, the corresponding lines are not necessarily parallel.
5. While the above conclusions are limited to the alloys which were considered, they are believed to be applicable to metals and alloys in general.

DISCUSSION

Mr. Howard Scott[1] (*presented in written form*).—There is a material basis for the idea conveyed by the title of this paper that a relation exists between the creep and recrystallization characteristics of metals. For example, creep and recrystallization are both analogous functions of time and temperature. If such a relation exists, it should be expressible in quantitative form. Certain data in the literature support that view and accordingly are worthy of review as a contribution to the discussion of this paper.

In determining the elastic modulus of metals at high temperatures, Andrews[2] noted a sharp increase in the degree of plastic deformation with increasing temperature. This temperature is evidently a significant temperature representative of the metal with respect to creep and corresponds with the "relaxation temperature" defined and evaluated in a somewhat different manner by the writer.[3] Andrews showed that this temperature in pure metals is a nearly constant fraction of the melting point on the absolute temperature scale. Presuming a close relation between recrystallization and creep, one should expect the recrystallization temperature to be similarly related to the relaxation temperature.

Use of the terms relaxation and recrystallization temperature is not intended to infer that they are well-defined properties of metals. The fact remains, however, that there are wide differences among metals as regards the temperature at which creep or recrystallization proceeds at a certain rate under comparable conditions and that these differences are of practical significance. Both variables are functions, possibly continuous ones, of previous treatment, temperature, time or load or degree of cold work. Hence, to distinguish quantitatively between metals on this basis, we must maintain at arbitrarily chosen values the variables other than temperature. The practical usefulness of the test data so obtained is the chief justification for the concepts of relaxation and recrystallization temperature.

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[1] Section Engineer, Research Laboratories, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[2] J. P. Andrews, "The Variation of Young's Modulus at High Temperatures," *Proceedings*, Physical Soc. London, Vol. 37, p. 169 (1924).

[3] Howard Scott, "High-Temperature Characteristics of Metals Revealed by Bending," *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part II, p. 129 (1931).

Data on the recrystallization of pure metals is scarce, but sufficient is given by Jeffries and Archer[1] for the announced purpose. The ratios of their values for 11 metals to the respective melting points on the absolute temperature scale fall between 0.35 and 0.51. This is excellent concordance considering the variations in purity and preparation to be expected. Since a very wide range of melting points is involved—magnesium to tungsten—the relation is most probably an exact one.

The relaxation and recrystallization temperatures being constant fractions of the absolute melting points of pure metals, it follows that one is proportional to the other. The value of Andrews' ratio is about 0.47 so one must be equal to the other or nearly so. Such a relation would be of great utility if applicable to alloys. We know, however, that the ratio of either property to the melting point must rise when an alloying element is added to a pure metal, the melting point being lowered by the alloying addition. Both the relaxation temperature and recrystallization temperature are raised by the alloying addition and consequently contribute further to the increase in the ratio. The ratio of one to the other, however, is not necessarily disturbed by alloying in view of certain other considerations.

From their close relation with the melting points of pure metals, it appears that both the relaxation and the recrystallization temperatures are manifestations of some more deep-seated and less accessible property such as internal friction. If so they should be influenced in the same manner by alloying additions. Evidence of this is furnished by Chevenard's[2] data on internal friction as modified by temperature and composition. He gives curves showing the temperature at which internal friction reaches an arbitrary value plotted against composition. The property measured is obviously the relaxation temperature with which we are concerned. It rises rapidly, but at diminishing rate with increasing small contents of nickel in copper. The recrystallization temperature varies in just the same manner with composition. Consequently, it is probable that the constant ratio of relaxation temperature to recrystallization temperature found in pure metals is carried over into alloys. At least the possibility is worthy of attention.

The paper under discussion provides material for testing the validity of the relation just presented. It is necessary first, however, to evaluate the relaxation temperature of the alloys tested as that has not been done by the authors. This was accomplished by plotting their values for the logarithm of the rate of creep at 10,000 lb. per sq. in. load against test temperature. By interpolation, the temperature at which the rate of creep equalled 1.0 per cent in 1000 hours was found and taken as the relaxation temperature.

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[1] Jeffries and Archer, "The Science of Metals," McGraw-Hill Book Co., Inc., New York City (1924).

[2] Pierre Chevenard, "The Mechanical Properties of Metals at Elevated Temperatures," Symposium on Effect of Temperature on the Properties of Metals, published jointly by the American Society for Testing Materials and The American Society of Mechanical Engineers, p. 245 (1931).

The relaxation temperature so defined for the hot-rolled alloys is plotted against recrystallization temperature as measured by the permanent softening of cold-rolled alloys in the accompanying Fig. 1.

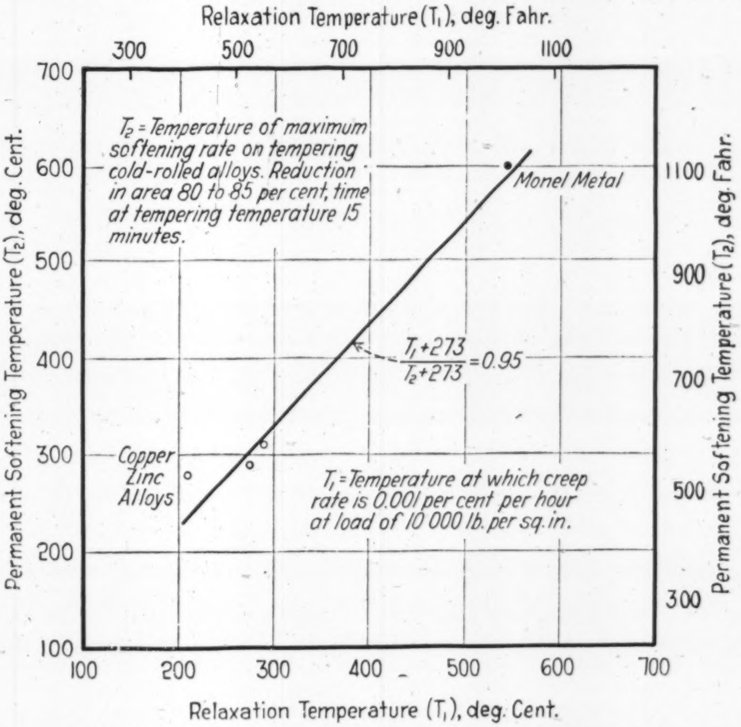

FIG. 1.—Relation of Recrystallization Temperature as Measured by Permanent Softening to Relaxation Temperature of Some Non-Ferrous Alloys.

The relaxation temperatures of the copper-base alloys are all close together, but data on monel metal which has a much higher relaxation temperature was available in a previous paper by the authors and was used. The permanent softening temperatures were taken from the writer's unpublished data on alloys. They were determined by plotting the hardness of the alloys as cold-worked with a reduction in area of 80 to 85 per cent against tempering temperatures at which the specimens were held for 15 minutes and taking the temperature of maximum slope.

If the generalization deduced from observations on pure metals holds for alloys, the plotted points should fall close to a straight line having a slope close to unity and this they do. The slope of the curve is 0.95. Of course the number of observations is small, but their conformity with expectation creates a strong presumption in favor of an exact relation.

Assuming this relation to be valid, their value in creep testing deserves comment. Instead of testing all metals at some arbitrary temperature, much more significant information can be obtained by testing each metal at its easily determined recrystallization temperature or some predetermined fraction thereof. That temperature represents the highest temperature at which useful creep resistance is available. Tests made at such a characteristic temperature will simplify greatly comparisons between metals with respect to high-temperature strength. Accordingly, it is hoped that the authors will extend their observations to a greater variety of alloys for further confirmation of the relation proposed.

MR. ARTHUR MCCUTCHAN[1] (*presented in written form*).—The authors apparently are not primarily concerned with the presentation of new creep data in this instance, but rather with an analysis of tendencies exhibited by materials previously reported. The difference in characteristic behavior of certain non-ferrous metals below and above the lowest recrystallization temperature is a point of particular interest. The writer wishes to contribute something from a mathematical standpoint toward the end of emphasizing this difference in creep characteristics of a metal under the two conditions.

Where test values of stress corresponding to different rates of creep are found to lie on a straight line on a log-log plot, it is possible to determine the equation of the parabola which passes through these points. The parabola, so determined, when plotted on ordinary coordinate paper, reveals in many cases interesting creep characteristics. The writer purposes to show that definite differences in the behavior of material below and above the recrystallization range appear to be exhibited by parabolas constructed from the test data given in this and the authors' former paper.[2]

The authors have based their conclusions on the difference in slopes of lines drawn approximately through test values plotted on a log-log plot of stress *versus* rate of creep. While it appears reasonable that material below its recrystallization temperature may have a characteristically different slope on such a chart from that of material above that temperature, these differences in slope do not give any direct indication of cessation of creep in one case and continuous creep in the other as implied by the authors.

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[1] Engineer, Engineering Division, The Detroit Edison Co., Detroit, Mich.

[2] C. L. Clark and A. E. White, "Properties of Non-Ferrous Alloys at Elevated Temperatures," Fuels and Steam Power, *Transactions*, Am. Soc. Mechanical Engrs., Vol. 53, No. 8, p. 183 (1931).

The results of a large number of creep tests made by prominent creep investigators on both ferrous and non-ferrous metals have been found to lie approximately on straight lines when the logarithm of the stress is plotted against the logarithm of the rate of creep. This fortuitous straight-line relationship has led to the rather general practice of plotting creep test values directly on log-log paper. A straight line, drawn as nearly as possible through the test points, commonly is assumed as the correct locus of all other test points for a given material at that temperature.

If sufficient limitation is placed on the permissible extrapolation of test data by means of such a line, there is no particular objection to using this method, at least in preliminary plotting. It is possible, however, that in some instances this straight-line relationship on log-log paper is considered as a law rather than a chance condition which has been observed only over a limited range of creep rates. The tacit assumption that creep values on a log-log chart should lie on a straight line has doubtless prevented actual test values being published in some cases and in others has led to the practice of determining only a limited number of points.

Where test values of stress corresponding to different rates of creep do chance to fall on a straight line when plotted on log-log paper, the equation of the parabola through these points can be determined. This parabola permits necessary interpolation and reasonable extrapolation of the data, is easily plotted, and at the same time provides restraint on the tendency to "leap into the unknown" so prevalent on log-log charts.

The general equation of a parabola with an intercept on the OY axis is $y = a x^b + c$. For material below its recrystallization range, the value of the constant c, which determines the intercept on the OY axis, is found (at least for materials considered herein) to have a value which apparently gives an indication of the limiting creep stress. At temperatures above the recrystallization range the simple equation of a parabola $y = ax^b$ is found to fit the test data, no intercept on the OY axis being required. This relation apparently indicates that at temperatures above the recrystallization range, there is no limiting creep stress, that is, extremely small stresses should cause creep of measurable magnitude.

Where only two or three test values are available, it must be realized, of course, that no very definite conclusion can be drawn as to whether an intercept, hence a limiting creep stress value, does exist for a particular case. Consequently, the need persists for more tests at smaller rates of creep to establish this distinction between materials above and below their recrystallization temperatures.

The value of c for material below its recrystallization range might be read directly from a curve sketched through the test points on ordinary coordinate paper as the intercept on the OY axis. See the accompanying Fig. 2. But, in most cases, this would require extending the curve considerably beyond the limits of actual test. Having determined that the test points lie on a straight line on a log-log plot of stress *versus* creep rate, the value of c may be approximated as follows[1]:

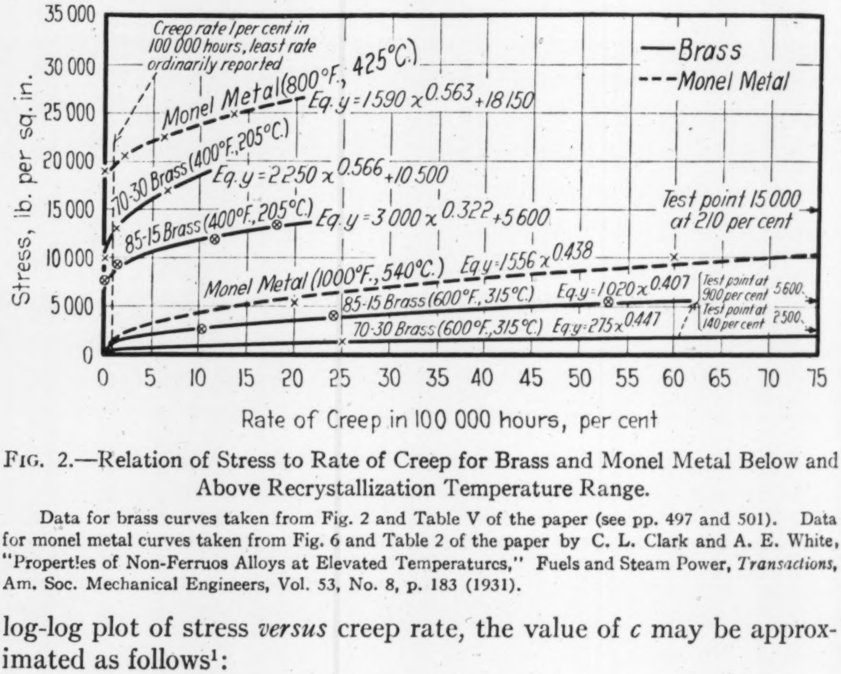

FIG. 2.—Relation of Stress to Rate of Creep for Brass and Monel Metal Below and Above Recrystallization Temperature Range.

Data for brass curves taken from Fig. 2 and Table V of the paper (see pp. 497 and 501). Data for monel metal curves taken from Fig. 6 and Table 2 of the paper by C. L. Clark and A. E. White, "Propert!es of Non-Ferruos Alloys at Elevated Temperaturcs," Fuels and Steam Power, *Transactions*, Am. Soc. Mechanical Engineers, Vol. 53, No. 8, p. 183 (1931).

"Choose two points (x_1, y_1) and (x_2, y_2) on the curve (see Fig. 2) sketched to represent the data. Choose a third point (x_3, y_3) on this curve such that $x_3 = \sqrt{x_1 x_2}$, and measure the value of y_3 from the curve. Then, since the three points are on the curve, their coordinates must satisfy the equation of the curve." From which:

$$c = \frac{y_1 y_2 - (y_3)^2}{y_1 + y_2 - 2\,y_3} \qquad \text{(1)}$$

After obtaining the value of c, the constants a and b are found by solution of simultaneous equations giving the relations of two points on the curve. These equations are found by writing the equation $y = ax^b + c$ in the form:

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[1] Joseph Lipka, "Graphical and Mechanical Computations," p. 140, John Wiley and Sons, Inc New York City (1918).

$$\log (y - c) = \log a + b \log x \quad \ldots\ldots (2)$$

As an example, consider the curve for 85–15 brass at 400° F., which is given on the authors' Fig. 2 of the present paper. Since the test points do not lie exactly on a straight line, there may be some question as to the particular location of the line on the chart, but for present purposes, the line as drawn on Fig. 2 may be considered as truly representing the data. Coordinates of two points on the curve are selected and a third point determined as outlined above. For convenience in calculation, the values of the abscissa of Fig. 2 are multiplied by 100, giving rate of creep in per cent per 100,000 hours.

The coordinates selected are as follows:

x_1	x_2	$x_3 = \sqrt{x_1 x_2}$	y_1	y_2	y_3
1	10	3.16	8 600	12 200	10 050

which from Eq. 1 above gives the value of $c = 5600$.

The constants a and b are found from the coordinates of two points on the curve:

x	y	$(y-c)$	$\log x$	$\log (y-c)$
1	8 600	3 000	0	3.47712
10	12 200	6 600	1	3.81954

$$\begin{array}{r@{\;=\;}l} 3.81954 & \log a + 1 \times b \\ \underline{3.47712} & \underline{\log a + 0 \times b} \\ \hline 0.32242 & b \\ \log a & 3.47712 \\ a & 3000 \end{array}$$

The equation of the parabola corresponding to the straight line for 85–15 brass at 400° F. is therefore $y = 3000\,x^{0.322} + 5600$.

Where the test points deviate materially from a straight line on log-log plotting, both the reasoning which permits extrapolation by means of a straight line and the use of a parabolic curve to check the character of the creep results are of doubtful significance. If the straight line of the authors' Fig. 2 does sufficiently well represent the creep characteristics of 85–15 brass at 400° F., then this alloy should be able to carry a load corresponding to a stress of approximately 5600 lb. per sq. in. without evidence of creep at 400° F. Actually, a stress of 7500 lb. per sq. in. was sustained by the test specimen without measurable creep. (See authors' Table V for load carried without measurable flow.)

In the same manner the constants for the curve 85–15 brass at 600° F. were determined. The simple equation of the parabola with its origin at the point (0,0) is found to fit the test data in this case, from which $y = 1020\, x^{0.407}$. This equation would indicate, as shown on Fig. 2, that at a temperature of 600° F. the least possible stress would cause some continuous creep. While this is not verified experimentally in the paper, a stress of only 2600 lb. per sq. in. is shown to cause extension at the rate of 10 per cent in 100,000 hours.

The curves of 70–30 brass at 400 and 600° F. show the difference in creep characteristics below and above the recrystallization range even more strikingly when the parabolas corresponding to the test points are plotted.

The test points for 70–30 brass at 400° F. give a calculated intercept on the OY axis of 10,500 lb. per sq. in. As only two points are given for this material at 400° F., and as very slight deviations from the particular line greatly affect the value of the calculated intercept, too much reliance should not be placed on such a value. However, it is interesting to note that a test load of 10,000 lb. per sq. in. did not give evidence of flow. (See authors' Fig. 2 and Table V.) These results again confirm the authors' prediction that at temperatures below the recrystallization range, comparatively large stresses can be sustained without practical manifestations of creep.

The 70–30 brass at 600° F. was found to flow at high rates even with very small loads, a load of only 1200 lb. per sq. in. giving a creep rate of 25 per cent in 100,000 hours, while a stress of 5600 lb. per sq. in. caused the specimen to extend at the rate of nearly 1 per cent in 100 hours. The parabola representing the line drawn to approximate the test points indicates that a stress of only 275 lb. per sq. in. would cause creep at the rate of 1 per cent in 100,000 hours. Hence, for practical purposes, it is apparent that this particular alloy should not be used for temperatures as high as 600° F.

In order to test whether any particular significance can be attached to the observation that creep values for materials below the recrystallization range require an equation of one type, while material above that range may be represented by another, the test values for monel metal at 800° F. are plotted on Fig. 2. From the authors' Fig. 6 of their paper on Properties of Non-Ferrous Alloys at Elevated Temperatures[1] it is noted that the test points fall close to the mean line. The value of the intercept on the stress axis is calculated as 18,150 lb. per sq. in. As indicated in the authors' Table 7 of that paper, there was no measurable creep found with a load of 18,780 lb. per sq. in.

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[1] *Loc. cit.*

At a temperature of 1000° F., which is above the recrystallization temperature for monel metal, as given in the authors' Table 2 of the same paper, the simpler equation involving only two constants is again found to closely approximate the test values. The least load applied, 5200 lb. per sq. in., gave an observed creep rate of 20 per cent in 100,000 hours.

If the same distinction in the behavior of ferrous metals below and above their recrystallization temperatures can be made by means of parabolas corresponding to the test points, the method proposed herein would be of more general significance. The practical difficulty in analyzing creep data on this basis lies in the fact that the actual recrystallization temperature is not available for most materials and the further fact that the majority of creep testing on ferrous metals has been done at temperatures well above the recrystallization temperature.

The advantages of the method of presenting creep data described in the foregoing discussion may be summed up as follows: (1) It affords a clearer picture of the relation of stress to rate of creep, as increments of stress and rate of creep have the same value at all portions of the curves. (2) It seems to make a fairly reliable distinction between the creep characteristics of material below and above the recrystallization temperatures, although too great reliance cannot be placed on this feature as in many cases whether an intercept exists or not cannot be ascertained from the few test points given. (3) It provides a natural restraint on the range of permissible extrapolation of test data.

MR. C. L. CLARK[1] (*authors' closure*).—Mr. McCutchan's mathematical treatment is very interesting and affords further proof of the authors' claims that at temperatures below the lowest temperature of recrystallization, stresses of definite magnitude are required to produce continuous creep, while at temperatures above this apparently critical temperature continuous creep will be obtained with any stress regardless of its magnitude. This method of treating creep results should be very valuable in all cases in which straight lines are obtained when the creep results are plotted on log-log coordinates.

Mr. Scott has brought out the fact that a relatively constant ratio exists between the melting point and the lowest temperature of recrystallization of pure metals. This relationship, however, does not hold for the usual types of commercial alloys. Small amounts of impurities often exert a much greater effect on the recrystallization temperature than on the melting point. Some work done in Germany a few years ago showed that the recrystallization temperature of pure silver could be varied appreciably by the additions of very small amounts of sulfur. The same is without doubt true for all the common alloying elements although very little information is available on this question.

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[1] Research Engineer (Metallurgy), Department of Engineering Research, University of Michigan, Ann Arbor, Mich.

As the authors have stated several times in the past, they are heartily in accord with the suggestion made by Mr. Scott that much time could be saved in creep testing work if the recrystallization temperature of the alloy to be tested were first determined and then creep tests conducted only on temperatures within this range. The authors feel that in the development of alloys for high-temperature service the first step should be to increase the recrystallization temperature to a point somewhere near the desired operating temperature range. In this connection it is regrettable that so little information is available concerning the effect of various alloy additions on the recrystallization temperature of steel. It is felt that this is a field which should receive much consideration during the next few years.

FACTORS AFFECTING THE PHYSICAL PROPERTIES OF CAST RED BRASS (85 Cu, 5 Zn, 5 Sn, 5 Pb)[1]

By H. B. Gardner[2] and C. M. Saeger, Jr.[3]

Synopsis

An investigation was sponsored by the Non-Ferrous Ingot Metal Institute at the U. S. Bureau of Standards to collect data upon which to base further work on bringing about agreement upon an optimum number of typical compositions of copper-base ingot metals. In the present paper all work has been restricted to the alloy having the nominal composition of 85 per cent copper, and 5 per cent each of zinc, tin and lead.

Four distinct types of test bars were cast at each of five pouring temperatures, 1900, 2000, 2100, 2200, and 2300° F. (1040, 1095, 1150, 1205, and 1260° C.) Tensile strength, Brinell hardness, electrical resistivity and density were determined on each bar and the results compared. These results permitted the grouping of the different test bars into three classes: first, the bars from the chill ingot; second, ingots obtained by the "immersed crucible" method; and third, the sand-cast bars. Only slight variations were found between the values obtained for test bars of virgin metal and corresponding bars made of remelted metal. The shrinkage and the running qualities of the alloy were determined for the alloy made from both virgin metal and remelted metal. The metallographic structure of the bars poured at the higher pouring temperatures lead to the conclusion that, in general, marked columnar structure is accompanied by inferior physical properties. Pronounced non-uniformity of structure was found in one type of sand-cast test bar. Microscopic examination tended to show that sand-cast test bars poured at high temperatures were subject to high tensile cooling stresses and had inferior physical properties. It was noted that an expansion of the alloy occurred immediately following solidification.

Introduction

In a survey made in 1929 by the Society's Special Committee on Promotion of General Use of Specifications for Copper Alloys in Ingot Form, it was found from data collected by the Non-Ferrous Ingot Metal Institute that the 600 copper-base alloy compositions used commercially might be grouped into 20 classes. It was hoped that, eventually, each class might be represented by one composition.

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[1] Publication approved by the Director of the Bureau of Standards of the U. S. Department of Commerce.

[2] Research Associate of the Non-Ferrous Ingot Metal Institute at the U. S. Bureau of Standards, Washington, D. C.

[3] Physicist, U. S. Bureau of Standards, Washington, D. C

As the Non-Ferrous Ingot Metal Institute had previously pledged its support, the Special Committee recommended that the Institute sponsor an investigation of copper-base ingot metals. The purpose of the investigation was to obtain data upon which to base further work of bringing about agreement upon an optimum number of typical compositions of copper-base ingot metal and to develop equitable standard specifications for the different classes. Subsequently the Non-Ferrous Ingot Metal Institute discussed with the U. S. Bureau of Standards the desirability of conducting such an investigation at the Bureau. A research associate was appointed by the Institute to work on this investigation, the Institute being represented by an Advisory Committee composed of Messrs. G. H. Clamer, F. L. Wolf and J. W. Bolton. Work was started in June 1930.

SCOPE OF INVESTIGATION

In drawing up the tentative program, the advisory committee suggested that, since red brass, of the nominal composition, 85 per cent copper and 5 per cent each of zinc, tin and lead, is one of the most widely used commercial alloys, it be selected as the alloy for starting this investigation.[1] It was recognized at the outset that a number of important variables must be studied. These included the form and method of casting the test bars, pouring temperatures, and slight differences in composition as represented by the use of virgin metal, remelted metal, and the addition of definite amounts of added impurities. It was recognized that no particular type of test bar in use is accepted as standard by the industry and perhaps no one test bar will prove suitable for all the classes of alloys. It is certain that no single pouring temperature could be arbitrarily recommended for use for all the different classes.

This paper summarizes the results obtained in the study of the physical properties as affected by pouring temperature and form of test bar, of the 85-5-5-5 alloy made from virgin metals and from remelted metals. Four distinct types of test bars, as described below, were poured in duplicate at each of five pouring temperatures, 1900, 2000, 2100, 2200, and 2300° F. (1040, 1095, 1150, 1205, and 1260° C.). The following properties were determined in sequence on each bar: electrical resistivity, tensile properties, density and Brinell hardness. In addition, the shrinkage, from the maximum pouring temperature to room temperature, and the running properties, for each of the five pouring temperatures, were determined for the alloys made from virgin metals and from remelted metals. Observations to determine the structural condition were also carried out.

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[1] Throughout this report the alloy has been designated as "red brass" in conformity with the practice of the Society as expressed in the Tentative Specifications for Copper-Base Alloys in Ingot Form for Sand Castings (B 30 - 31 T), see *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part I, p. 703 (1931); also 1931 Book of A.S.T.M. Tentative Standards, p. 135. The name "bronze" is often used commercially, however, for example, U. S. Master Specification No. 172a, Federal Specifications Board.

MATERIALS AND METHODS OF CASTING TEST SPECIMENS

Materials:

The virgin metals used for making all the alloys were analyzed chemically. The only significant impurities were 0.0052 per cent of iron in the copper, 0.01 per cent of iron in the zinc, 0.016 per cent of iron and 0.12 per cent of bismuth in the lead, and 0.023 per cent of iron in the tin. The alloys were made up in heats varying from 80 to 100 lb., the amount of the constituent metals being weighed to the nearest ounce. The chemical composition was determined for each alloy. The range of composition of the various heats was as follows:

	COPPER, PER CENT	TIN, PER CENT	LEAD, PER CENT	ZINC, PER CENT BY DIFFERENCE
Virgin metals.......	84.52 to 85.56	4.91 to 5.26	4.80 to 5.28	4.64 to 5.21
Remelted metals	84.45 to 86.06	4.91 to 5.23	4.77 to 5.25	4.50 to 5.42

Molding, Melting and Pouring:

The metal was melted in a high-frequency induction furnace of the "lift-coil" type in a double-wall clay-graphite crucible. Each melt, to be poured at a definite pouring temperature, was heated to a temperature 100° F. (55° C.) higher than this. The double-wall crucible was necessary in order to maintain the desired temperature during the pouring of the series of test bars to be cast. The greatest difference in the pouring temperature between the first and last of a series was 10° F. (6° C.) at 1900° F. (1040° C.) and approximately twice as great at 2300° F. (1260° C.).

Green-sand molds prepared from grade 00 Albany sand were used. Permeability of 12 to 16 and compressive strength of 5 to 7 (expressed in American Foundrymen's Association units) were maintained with a moisture content of 6 to 6½ per cent.

Types of Test Bars:

Two forms of sand-cast bars, a chilled ingot, and an ingot obtained by immersing a graphite crucible beneath the surface of the molten metal, were made from each heat.

Fin-Gate Sand-Cast Bar.—This test bar, often designated as the Webbert bar, is shown in Fig. 1. Its use is required in the specifications of the Society for brass castings.[1] Web thicknesses of $\frac{1}{8}$, $\frac{3}{16}$ and $\frac{1}{4}$ in. were used.

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[1] Standard Specifications for Composition Brass or Ounce Metal Sand Castings (A.S.T.M. Designation: B 62 – 28), 1930 Book of A.S.T.M. Standards, Part I, p. 678.

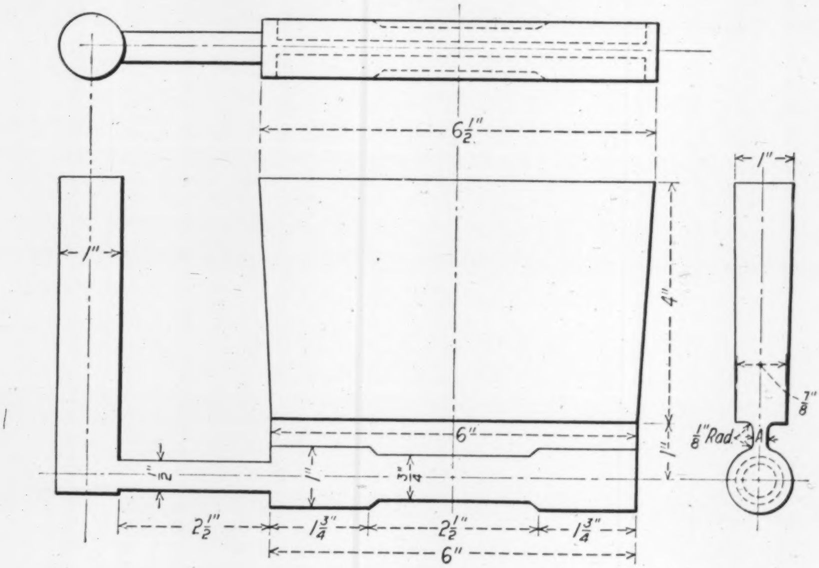
6½"
1"
4"
1"
6"
½"
1"
¾"
2½"
1¾"
2½"
1¾"
6"
1"
⅞"
⅛" Rad.
A

FIG. 1.—Sand-Cast Test Bar Designated as the "Fin-Gate" Type. The thicknes of the web, A, was varied as follows: $\frac{1}{4}$, $\frac{3}{16}$ and $\frac{1}{8}$ in.

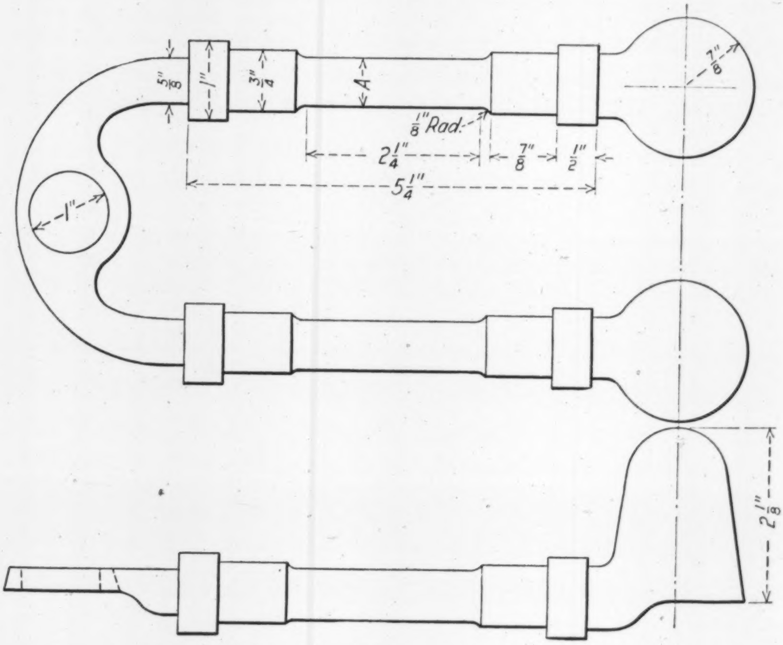
⅝"
1"
¾"
A
⅞"
⅛" Rad.
2¼"
⅞"
½"
5¼"
1"
2⅛"

FIG. 2.—Sand-Cast Test Bar Designated as the "End-Gate" Type.

In cast-to-size bar, $A = 0.505$ in.
In machined-to-size bar, $A = 0.625$ in.
To be poured uphill at an angle of 7 deg. with a 1-in. round pouring gate 5 in. high.

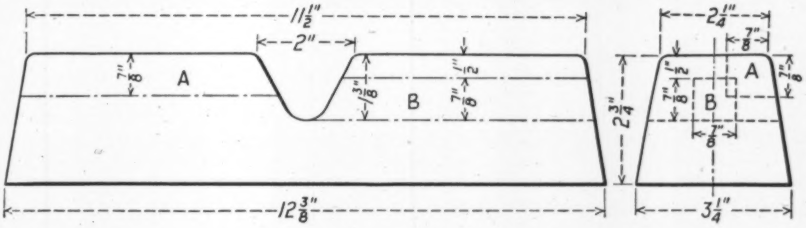
11½"
2"
A
B
7/8"
3/8"
½"
7/8"
2¾"
12⅜"
2¼"
7/8"
A
½"
7/8"
B
7/8"
7/8"
3¼"

FIG. 3.—Position of Test Bars from Chill-Cast Ingot: *A*, Two-Side Chill; *B*, No-Side Chill.

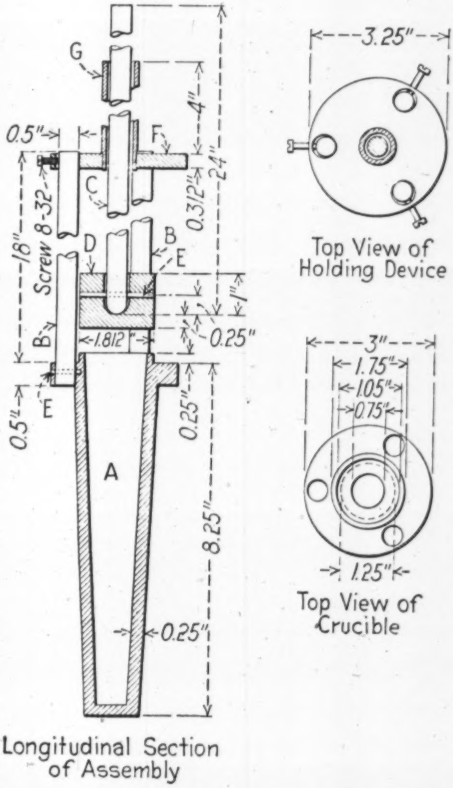
G
4"
24"
0.5"
F
C
Screw 8-32
0.312"
18"
D
B
E
1"
1.812
0.25"
B
E
0.5"
0.25"
A
8.25"
0.25"
Longitudinal Section of Assembly
3.25"
Top View of Holding Device
3"
1.75"
1.05"
0.75"
1.25"
Top View of Crucible

FIG. 4.—Device of Graphite Used for Obtaining Test Bars by the Immersed-Crucible Method.

The tightly closed crucible *A*, of known volume, was immersed beneath the surface of the molten metal and allowed to come to the temperature of the metal. The top, *E*, was then raised by means of the rod *C* and the crucible, *A*, was filled. The cover was then replaced and the device, together with the sample of metal contained, was removed, placed in a dry-sand mold and allowed to cool to room temperature. The ingot, *A*, was used in determination of shrinkage as well as in other tests.

End-Gate Sand-Cast Bar.—The characteristic features of this casting, shown in Fig. 2, are the absence of a heavy riser which seems to retard the cooling of the test specimen and that it furnishes two specimens poured under identical conditions. It was also selected for the purpose of studying the "skin effect" on the physical properties by comparing bars cast to size and machined to size. This type of bar has been used with pronounced success in commercial foundry work on non-ferrous alloys.[1]

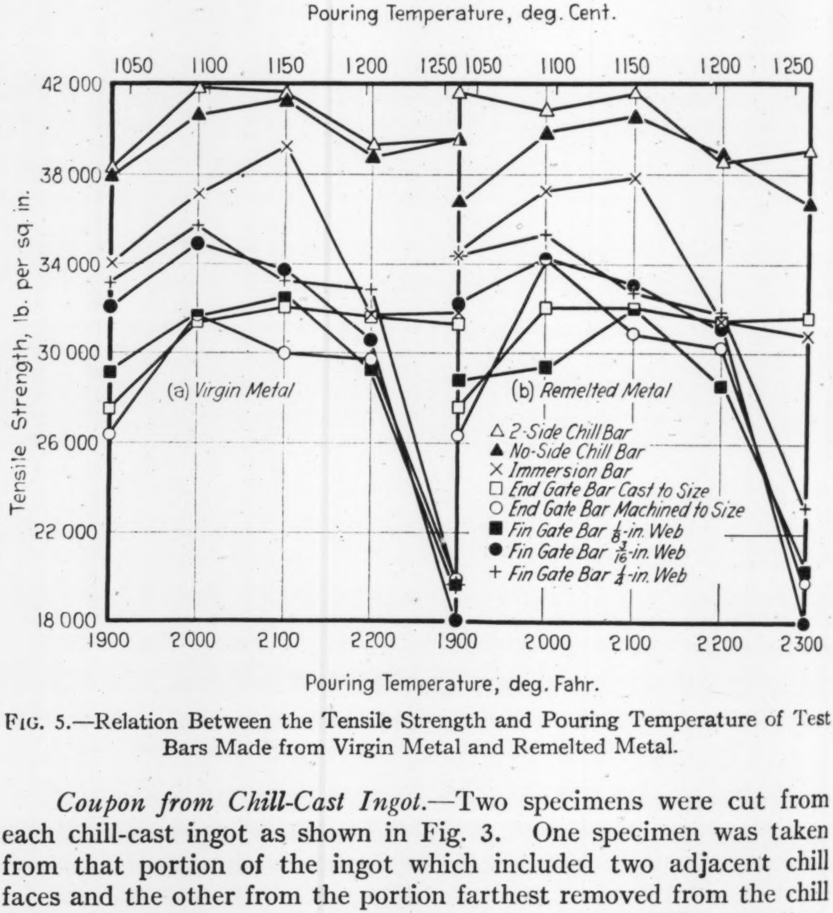

FIG. 5.—Relation Between the Tensile Strength and Pouring Temperature of Test Bars Made from Virgin Metal and Remelted Metal.

Coupon from Chill-Cast Ingot.—Two specimens were cut from each chill-cast ingot as shown in Fig. 3. One specimen was taken from that portion of the ingot which included two adjacent chill faces and the other from the portion farthest removed from the chill faces. These have been designated as "two-side chill" and "no-side chill," respectively.

Coupon from "Immersed Crucible" Ingot.—This method, which consists essentially in withdrawing a sample of metal by means of a graphite crucible submerged beneath the surface of the liquid metal, is illustrated in Fig. 4. This method permitted the sampling of any heat without contamination from the moisture of sand molds. The "gassing" of metals and the source of the contamination are questions of interest to the foundry industry. This method permits comparison to be made between metal as ordinarily cast and the same metal not subjected to pouring and mold conditions.

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[1] R. W. Parsons, "Deep Etching of Brass Applied to Gating Problems," *Transactions*, Am. Foundrymen's Assn., Vol. 39, p. 843 (1931).

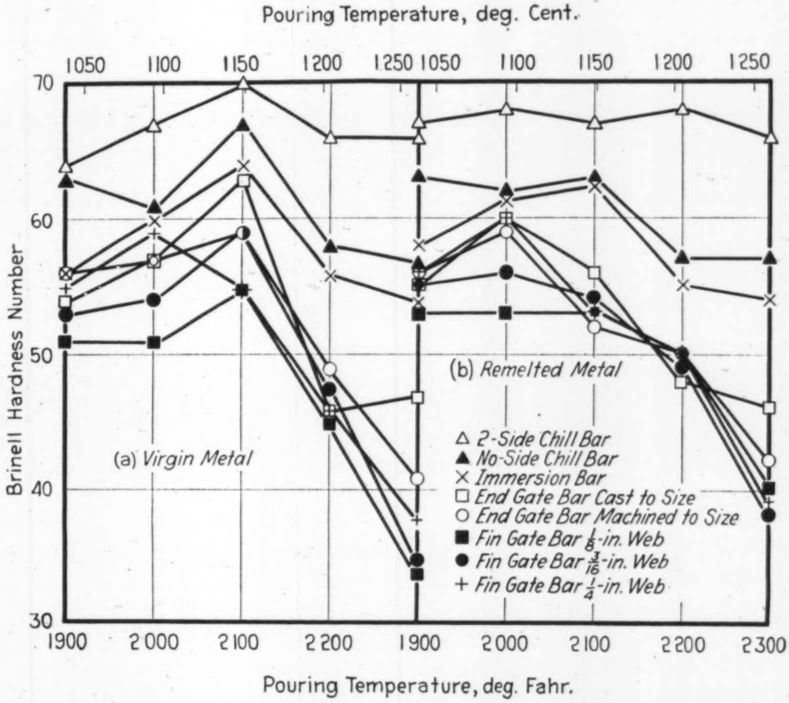

FIG. 6.—Relation Between the Brinell Hardness and Pouring Temperature of Test Bars Made from Virgin Metal and Remelted Metal.

This method was used on each crucible of metal before the other forms of test bars were cast. The ingot obtained served a double purpose in that it furnished data on the shrinkage of the liquid metal and it was later machined to a conventional test specimen form for determining the physical properties.

RESULTS AND DISCUSSION

Tensile Strength:

The tensile properties were determined with an Amsler universal testing machine of 50,000 lb. capacity, the load being applied at a uniform rate for all bars. The standard test specimen 0.505 in. in diameter, with threaded ends and a 2-in. gage length was used. Only the values for ultimate tensile strength are reported here and are given in Fig. 5.

For each type of test specimen, superior tensile strengths were obtained on those poured at 2000 or 2100° F. (1095 or 1150° C.). A marked drop in tensile strength was observed for the machined sand-cast specimens poured at 2300° F. (1260° C.). No pronounced beneficial "skin-effect" on cast-to-size specimens was observed except for bars cast at the high pouring temperature. On the basis of tensile strength the various types of test specimens may be arranged in three groups. The highest tensile strength was obtained on specimens cut from the chill-cast ingots. Next in order were those cut from the immersed-crucible ingots. The sand-cast bars, with the exception noted above, were uniformly lower in their tensile strength. No important or significant differences were noted for the virgin and the remelted metal.

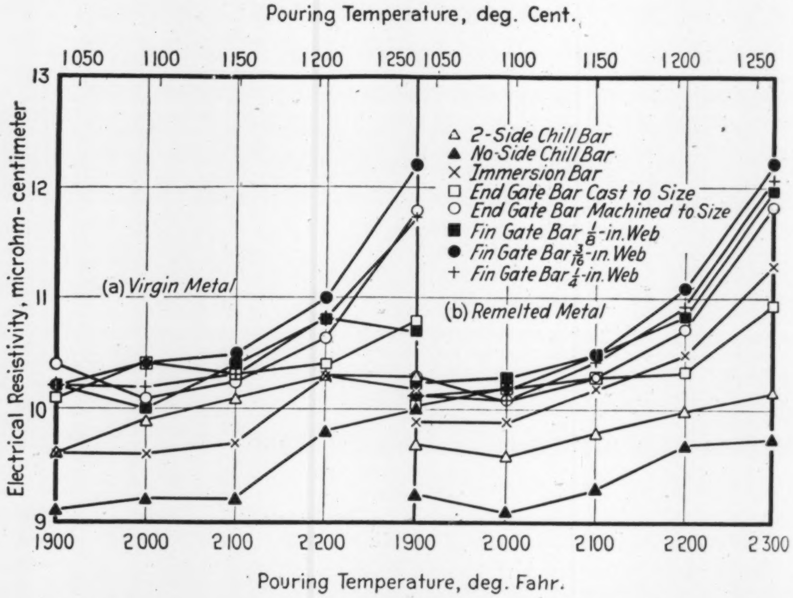

FIG. 7.—Relation Between the Electrical Resistivity and Pouring Temperature of Test Bars Made from Virgin Metal and Remelted Metal.

Brinell Hardness:

Brinell hardness determinations were made on flat faces, $\frac{5}{8}$ in. in width, machined on the side of the threaded portion of the broken tension test specimens. The results are shown in Fig. 6, each plotted point being the average of three determinations. The curves for Brinell hardness of the different test specimens obtained at the different temperatures show the same general trend as the corresponding

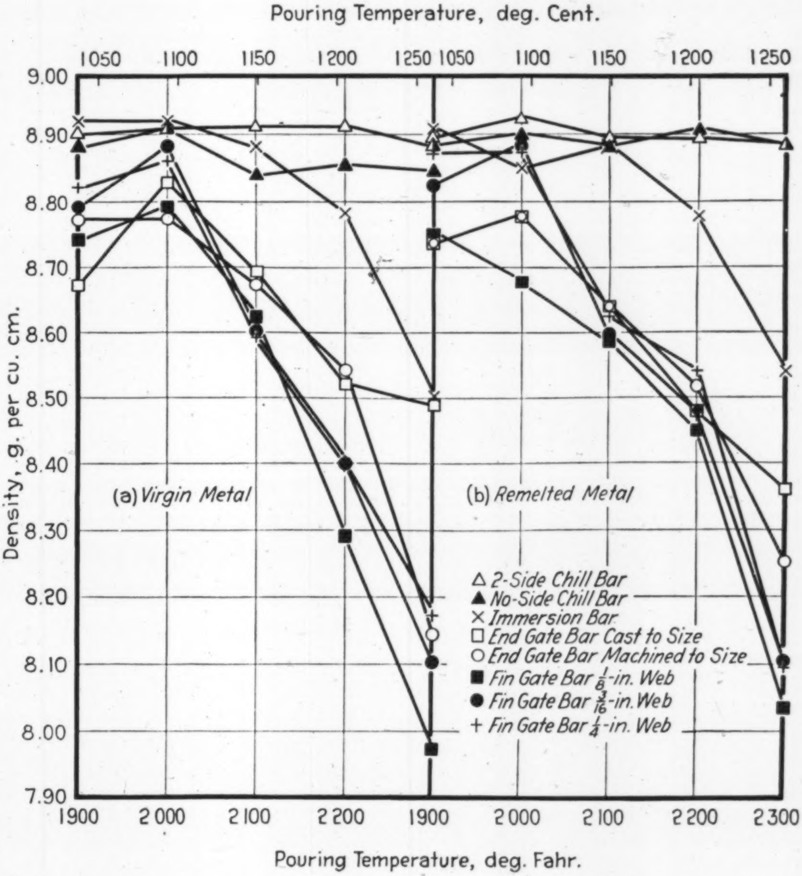

FIG. 8.—Relation Between the Density and Pouring Temperature of Test Bars Made from Virgin Metal and Remelted Metal.

curves for tensile strength, the grouping of the test specimens on the basis of hardness being the same as that based on tensile strength

Electrical Resistivity:

The determination of electrical resistivity was made on the specimens used subsequently for tension tests in order to facilitate correlation between these different properties. These determinations[1] were carried out according to the procedure recommended by this Society.[1] The results shown in Fig. 7 are, in general, in good agreement with those for tensile strength and hardness. The specimens having superior tensile strength and hardness showed lower resistivity. The resistivity increased decidedly as the pouring temperature was increased above 2100° F. (1150° C.). This change in resistivity was more uniform for the remelted metal than for the virgin metal.

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[1] Made by J. L. Thomas, Associate Physicist, U. S. Bureau of Standards, Washington, D. C.

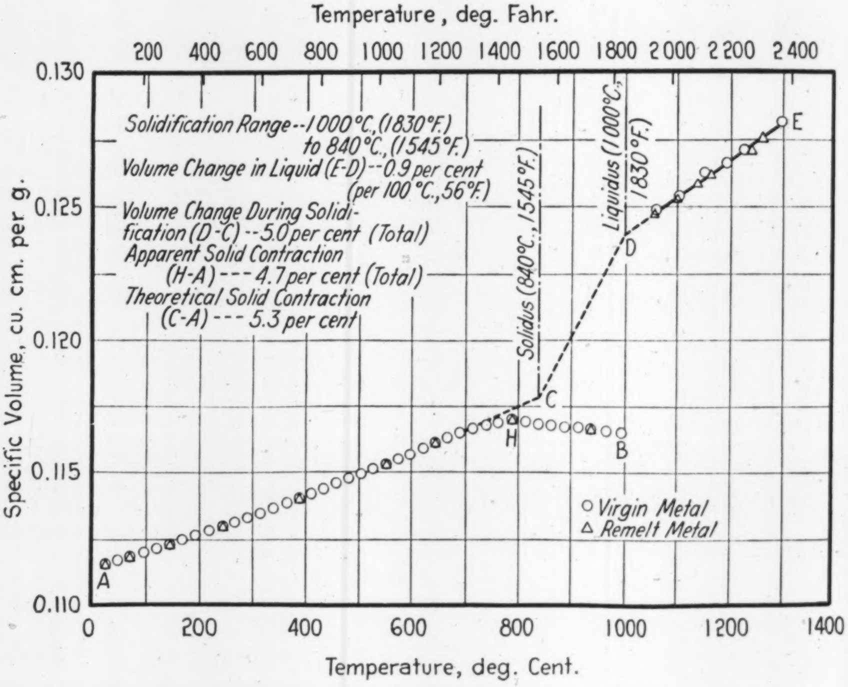

FIG. 9.—Shrinkage of Red Brass from 1300° C. (2370° F.) to Room Temperature.

Density:

The density was determined by displacement of water by the ends of the broken test specimens. These specimens were later employed to measure the hardness. The results are given in Fig. 8. No very marked differences in density between the virgin and the remelted metals were found. All of the sand-cast bars showed a very marked decrease in density as the pouring temperature was increased, whereas the density of specimens cut from the chilled ingots which was uniformly higher than that of sand-cast bars was independent of pouring temperature. The density of specimens obtained by the immersed-crucible method, for pouring temperatures of 2200° F. (1205° C.) and above, was intermediate between the corresponding values for the chilled ingot and the sand-cast bars. The results show that the maximum density was obtained in practically all cases with a pouring temperature of 2000° F. (1205° C.).

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[1] Standard Method of Test for Resistivity of Metallic Materials for Resistors (A.S.T.M. Designation: B 63 – 29), 1930 Book of A.S.T.M. Standards, Part I, p. 869.

Shrinkage:

The shrinkage of the alloy from a temperature (2400° F., 1315° C.) exceeding the highest pouring temperature used (2300° F., 1260° C.) to room temperature was determined by the method described by Saeger and Ash.[1] The results which are expressed as changes in specific volume are given in Fig. 9. The shrinkage of the liquid metal (*E-D*, Fig. 9) was determined on ingots obtained by the immersed-crucible method. Data on the shrinkage of the solid metal (*C-A*, Fig. 9) were obtained by direct observations of the change in length with change of temperature of a special sand-cast rectangular bar. To determine the shrinkage during solidification (*D-C*) it was necessary to determine the solidus, *C*, and the liquidus, *D*, for this alloy. This was done by means of thermal analysis. An average value of 1000° C. (1830° F.) was obtained for the liquidus and 840° C. (1545° F.) for the solidus. The difference between the specific volumes corresponding to these temperatures is designated as shrinkage of solidification. No significant differences in shrinkage were observed between alloys made from virgin metal and from remelted metal.

There was observed, however, in determining the linear shrinkage of the solid metal, a definite expansion at temperatures just below the solidus. This is shown in Fig. 9 by the portion of the curve, *H-B*. To determine whether or not this expansion was the result of "gassing" of the metal from the charcoal which formed part of the protective covering used, charges were melted in both the induction furnace and in a gas-fired furnace for which a protective covering of fused sodium carbonate was used. The same phenomenon was found in all cases, in remelted as well as in virgin metal. These results are given in Fig. 10. The significance of and reason for this behavior are still uncertain.

Running Qualities:

The running qualities of the alloy were studied by the method described by Saeger and Krynitsky[2] which consists essentially in

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[1] C. M. Saeger, Jr., and E. J. Ash, "A Method for Determining the Volume Changes Occurring in Metals During Casting," Research Paper No. 399, U. S. Bureau of Standards *Journal of Research*, Vol. 8, No. 1, p. 37 (1932).

[2] C. M. Saeger, Jr., and A. I. Krynitsky, "A Practical Method for Studying the Running Quality of a Metal Cast in Foundry Molds," *Transactions*, Am. Foundrymen's Assn., Vol. 39, p. 513 (1931).

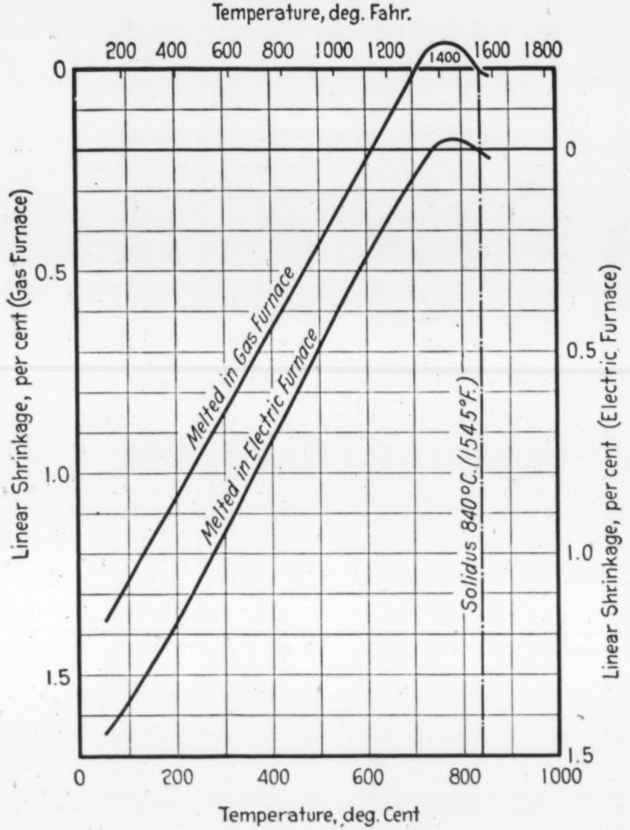


FIG. 10.—Linear Contraction of Red Brass from Solidification to Room Temperature.

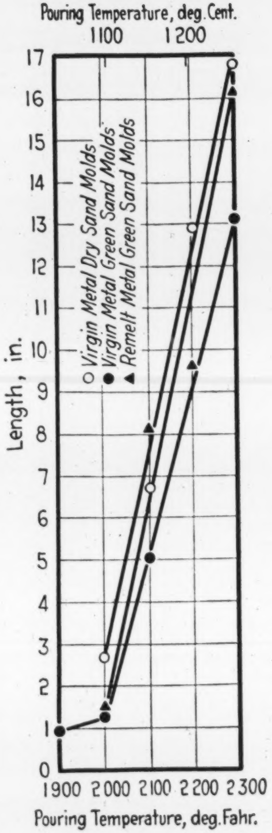


FIG. 11.—Running Properties of Red Brass Made from Virgin Metal and from Remelted Metal Cast in Sand Molds.

casting a strip of small cross-section in the form of a spiral. Both virgin and remelted metal were used and the results are given in Fig. 11. The remelted metal, cast in green sand, was more fluid than virgin metal cast under the same condition and only slightly less fluid than virgin metal cast in dry sand.

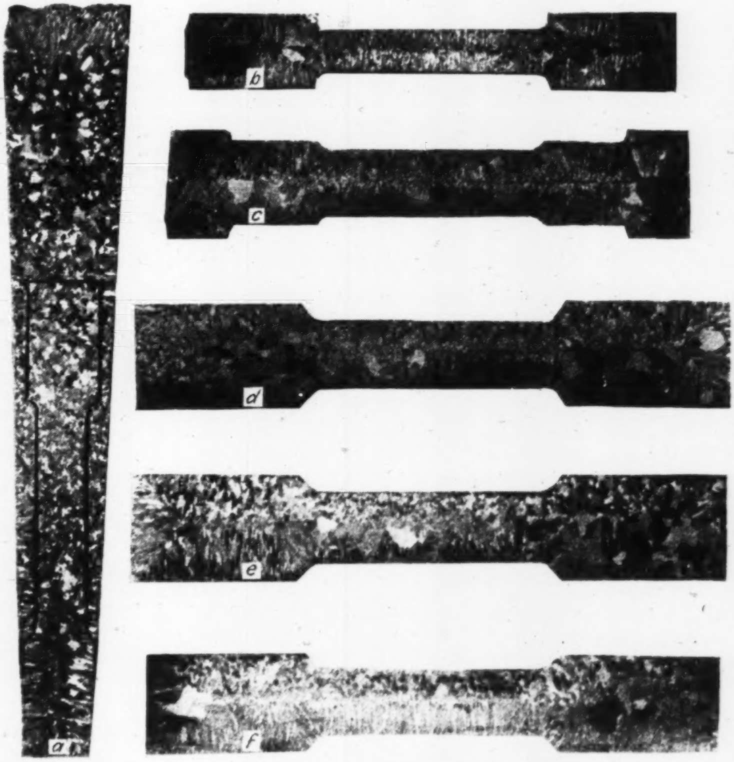


FIG. 12.—Longitudinal Cross-Section of Test Bars of Virgin Metal. Cast at 2200° F. (1205° C.). Macro-etched with ammoniacal solution of copper-ammonium chloride, reduced one-half in reproduction.

(*a*) Ingot obtained by immersed-crucible method.
(*b*) End-gate sand-cast bars, cast to size.
(*c*) End-gate sand-cast bars, machined to size.
(*d*) Fin-gate sand-cast bars, $\frac{1}{8}$-in. web.
(*e*) Fin-gate sand-cast bars, $\frac{3}{16}$-in. web.
(*f*) Fin-gate sand-cast bars, $\frac{1}{4}$-in. web.

Metallographic Structure:

In an endeavor to explain the reason for the pronounced influence of the pouring temperature on the physical properties of sand-cast bars and specimens obtained by the immersed-crucible method, the macrostructure of bars cast at 2200 and 2300° F. (1205 and 1260° C.)

was studied. Photographs of etched medial longitudinal sections, perpendicular to the parting line of the mold, are shown in Figs. 12 and 13. The tendency to the formation of a columnar crystalline structure in the bars cast at the higher temperature was much more pronounced than in the corresponding bars poured at the lower temperature. A comparison of these results with those previously given indicates that a marked columnar structure is accompanied by inferior physical properties.

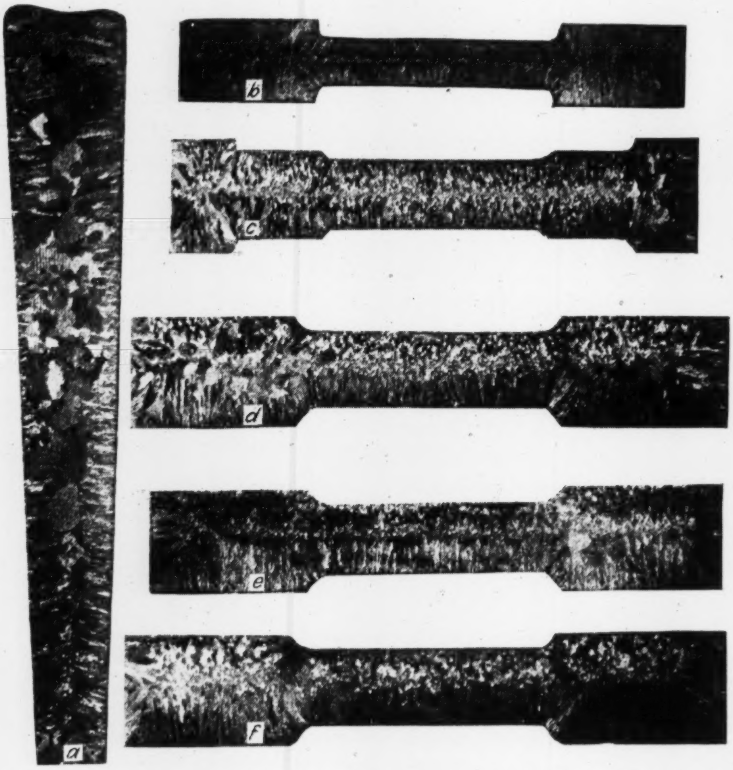
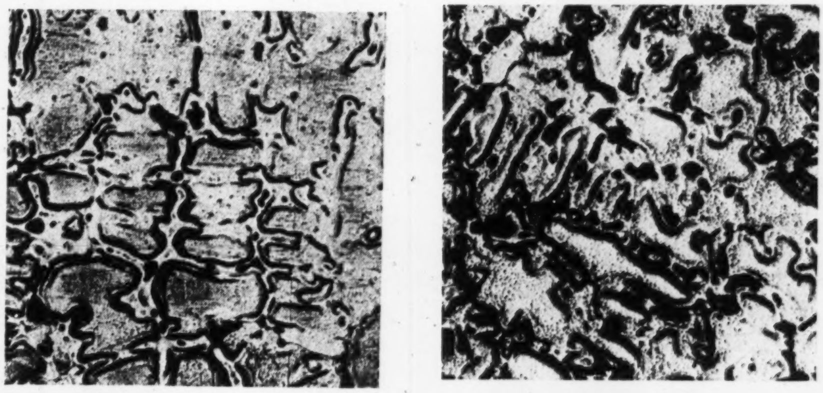


Fig. 13.—Longitudinal Cross-Section of Test Bars of Virgin Metal. Cast at 2300° F. (1260° C.). Macro-etched with ammoniacal solution of copper-ammonium chloride, reduced one-half in reproduction.

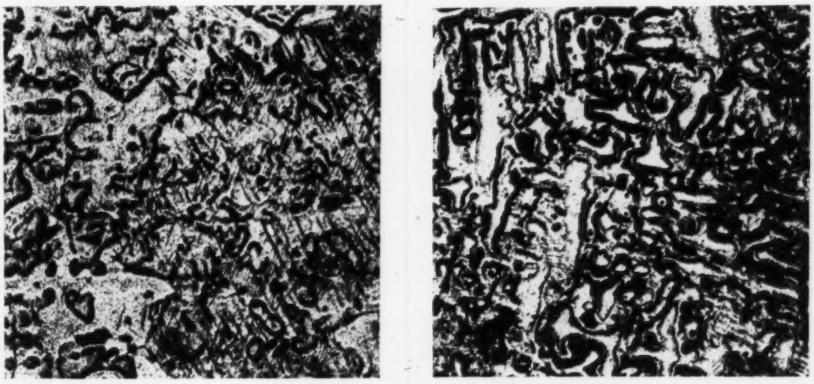
(*a*) Ingot obtained by immersed-crucible method.
(*b*) End-gate sand-cast bars, cast to size.
(*c*) End-gate sand-cast bars, machined to size.
(*d*) Fin-gate sand-cast bars, $\frac{1}{8}$-in. web.
(*e*) Fin-gate sand bars, $\frac{3}{16}$-in. web.
(*f*) Fin-gate sand-cast bars, $\frac{1}{4}$-in. web.

Very little difference in structure was found in sand-cast bars, cast to size; in both the columnar structure predominated. In the

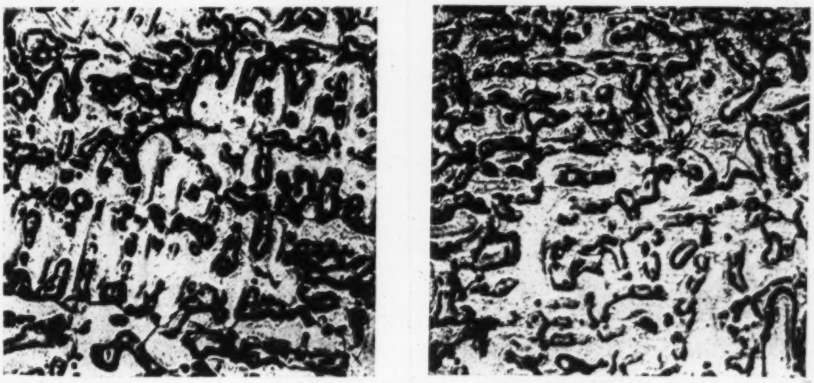
Poured at 2200° F. (1205° C.) Poured at 2300° F. (1260° C.)



(*a*) Ingot obtained by immersed-crucible method.



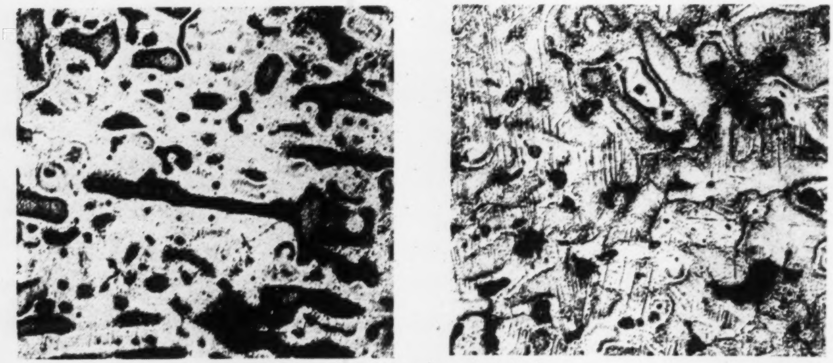
(*b*) End-gate sand casting, cast to size.



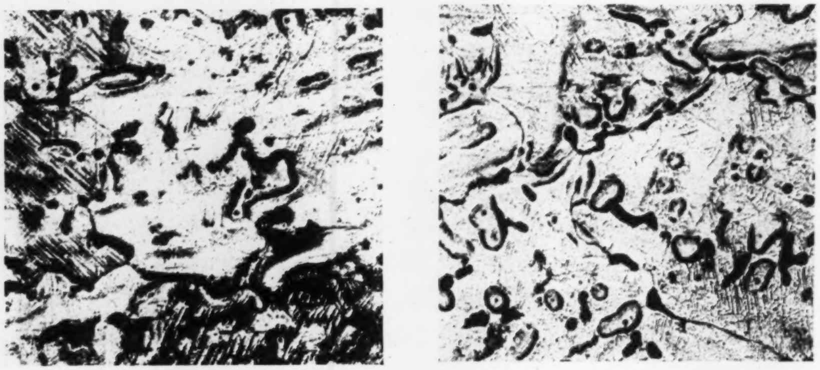
(*c*) End-gate sand casting, machined to size.

FIG. 14.—Microstructure of Test Bars of Virgin Metal Poured at 2200° F. (1205° C.) and 2300° F. (1260° C.) (× 100). Etching reagent, mixture of ammonium hydroxide and hydrogen peroxide.

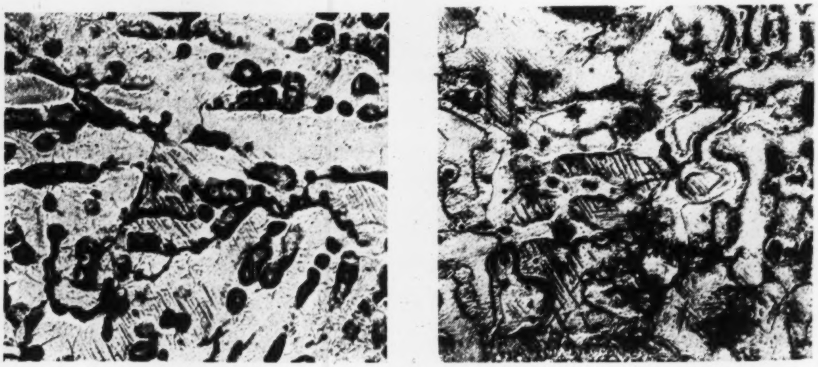
Poured at 2200° F. (1205° C.) Poured at 2300° F. (1260° C.)



(*a*) Fin-gate sand casting, $\frac{1}{8}$-in. web.



(*b*) Fin-gate sand casting, $\frac{3}{16}$-in. web.



(*c*) Fin-gate sand casting, $\frac{1}{4}$-in. web.

FIG. 15.—Microstructure of Test Bars of Virgin Metal Poured at 2200° F. (1205° C.) and 2300° F. (1260° C.) (× 100). Etching reagent, mixture of ammonium hydroxide and hydrogen peroxide.

larger specimens of this type, machined to size, the structural difference was more pronounced. In all of the fin-gate sand-cast bars, a marked non-uniformity of structure across the section of the bar existed. The portion of the bar formed in the "drag" of mold had a pronounced columnar structure, whereas the remainder, which was undoubtedly influenced by the relatively large mass of metal in the attached riser, was of an equiaxed crystalline structure. Such a marked non-uniformity of structure of a test bar is not desirable and should be avoided.

The observed differences in physical properties of bars obtained by the immersed-crucible method at 2200 and 2300° F. (1205 and 1260° C.) may be explained largely on the basis of the difference in grain size in the two cases.

The effect of pouring temperature on the microstructure of the various test bars is shown in Figs. 14 and 15. In each case the micrograph shows a distinctive area in the reduced section of the bar just within the inner surface layer of columnar crystals. In all of the sand-cast specimens, markings consisting of groups of parallel lines, within the individual grains were found which were considered to be the result of deformation or strain. This structural feature was not found in the bar obtained by the immersed-crucible method. This fact may be interpreted as indicating that no strains are set up in a bar of this kind on cooling such as may be the case with the sand-cast bars where the gates and risers are in a fixed position within the sand mold and thus result in the permanent straining of the bar by shrinkage during cooling probably while the metal is in a very "tender" condition immediately after solidification.

SUMMARY

The much-discussed question of the relative merits of "cast-on" and "separately-cast" bars has not been covered by this investigation. All of the bars used can be designated as "separately-cast."

The pouring temperature was found to have a marked influence on all the physical properties studied for the sand-cast bars. This effect was less pronounced for the specimens obtained by the immersed-crucible method and almost negligible for the specimens from the chill-cast ingots.

The best physical properties were obtained on those test bars poured at 2000 and 2100° F. (1095 and 1150° C.).

There was no marked difference in the physical properties of test bars made from virgin metal and from remelted metal. Somewhat better running qualities were obtained with remelted metal cast in green-sand molds than with virgin metal cast under the same conditions.

The physical properties obtained with the end-gate type of sand-cast test bars were in general superior to those obtained with the fin-gate type of bars. This statement also applies to the cast-to-size sand-cast test bars as compared to the machined-to-size sand-cast test specimens.

It was found that the test specimens having superior physical properties also showed more uniformity in their structure. Strain markings indicative of permanent straining as a result of cooling stresses were found in the microstructure of all of the sand-cast bars poured at the higher temperatures.

The shrinkage of the alloy was determined from a temperature above the highest pouring temperature used to room temperature. No difference was found in the shrinkage of the virgin and remelted metal. Determination of the linear contraction of a sand-cast bar showed a definite expansion just below the solidus temperature.

Acknowledgments:

This investigation has necessitated the extensive cooperation of all of the members of the Foundry Section and of others of the Bureau staff. Progress in the work has been greatly expedited by a high-frequency induction furnace of the "lift-coil" type, the use of which was donated by the manufacturers. All materials were furnished by the Non-Ferrous Ingot Metal Institute. An earnest effort has been made to meet the suggestions which the advisory committee has made from time to time as the work progressed, and it is felt that in this way the practical aspects of the problem have not been neglected.

DISCUSSION

Mr. H. M. St. John[1] (*presented in written form*).—The conclusions of the authors with respect to the influence of pouring temperature on the physical properties of sand-cast metal are of great interest and agree well with some of my own experiences and observations. I believe they are correct in attributing the weakness of hot cast metal to the coarse crystalline structure rather than to the gassed condition which is occasionally found in metal cast at excessive temperatures. If it is true that a coarse columnar crystalline structure results in low tensile strength and decreased elasticity, it follows that any factor which tends to produce such a structure will have a detrimental effect on the physical properties of the metal. This is probably true whether the structure is actually columnar or coarsely dendritic. There are factors other than temperature which tend to produce a dendritic structure, particularly the presence of such impurities as aluminum, magnesium, and silicon. On the other hand, other elements such as nickel or sulfur tend to produce a close grained structure and to counteract the influence of undesirable impurities if present. I am inclined to think that these facts offer an adequate explanation for some of the otherwise obscure difficulties which have been experienced by foundrymen with this and similar red brass alloys.

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[1] Metallurgist, Detroit Lubricator Co., Detroit, Mich.

MECHANICAL PROPERTIES OF WHITE-METAL BEARING ALLOYS AT DIFFERENT TEMPERATURES[1]

By H. K. Herschman[2] and J. L. Basil[3]

Synopsis

A study was made of the wear resistance and other mechanical properties of ten white-metal bearing alloys. These included two tin-base and seven lead-base alloys and one cadmium-zinc alloy. Each of the properties, with the exception of wear, was determined at several temperatures, ranging from 20 to 200° C. (68 to 390° F.). Resistance to wear was determined only at 20° C. (68° F.). No one of the alloys tested was found to excel in all of the mechanical properties studied. Thus, the tin-base alloys showed higher resistance to wear and in most cases had higher Izod impact values at each temperature of test than the lead-base alloys, but in most cases showed lower resistance to pounding than the lead-base and cadmium-zinc alloys. The hardness numbers and compressive properties of the tin-base alloys were found to be lower than those for the alkaline-metal hardened lead and the cadmium-zinc alloys. The mechanical properties of the lead-antimony-tin alloys were, in most cases, higher as the tin content was increased.

Crankshaft bearings of four compositions were prepared for service tests in U. S. Army class B trucks. These compositions consisted of two tin-base and two lead-base alloys. The results of these tests indicated that the tin-base alloys were superior in their wear resistance to the lead-base alloys. These results were consistent with those obtained on wear in the laboratory tests.

Introduction

The usual white-metal bearing alloys require tin or antimony, or both, as essential constituents. Both tin and antimony are so-called "strategic" metals[4] and the potential military demands for these metals are considerable. These facts were responsible for the sponsoring by the War Department of recent studies at the Bureau of Standards aimed towards the reduction of the amounts of tin and antimony needed for bearing alloys or possibly the elimination of such need by the development of suitable replacement alloys.

One phase of this work was a survey of some of the usual commercial white-metal bearing alloys, both tin-base and lead-base, and the determination of such of their mechanical properties as appear of chief significance in the service of such alloys in bearings. It is this phase of the work which is discussed in the present paper.

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[1] Publication approved by the Director of the Bureau of Standards of the U. S. Department of Commerce.

[2] Associate Metallurgist, U. S. Bureau of Standards, Washington, D. C.

[3] Junior Metallurgist, U. S. Bureau of Standards, Washington, D. C.

[4] Roger Taylor, "Strategic Raw Materials," *Metals and Alloys*, Vol. 1, p. 5 (1929).

Such data in the literature as deal with the mechanical properties of these white-metal bearing alloys refer for the most part to properties at approximately 20° C. (68° F.). While the properties and behavior of bearing metals at room temperature are of interest and may furnish much significant information, it is in reality the properties at higher temperature that play the major part in determining the success or failure of a bearing metal under service conditions. Previous work at this Bureau on some of the mechanical properties of lead-base and tin-base alloys at 20° C. (68° F.) and 100° C. (212° F.) has been reported by Freeman and Woodward[1] and Freeman and Brandt.[2] Ellis [3,4,5,6] determined the hardness of tin-base bearing alloys at temperatures up to 140° C. (285° F.) as well as the hardness and compressive properties of lead-base alloys at room temperature.

In a recent compilation of published data on the properties of bearing metals at elevated temperatures, Darby[7] called attention to the scattered and incomplete nature of this information. His paper also indicated a complete lack of data on the resistance to wear and impact of white-metal bearing alloys.

The present report gives data on the resistance to wear, to impact (Izod test), and to pounding (repeated impact), the strength in compression, and Brinell hardness of ten bearing alloys. These included two tin-base, seven lead-base alloys and one cadmium-zinc alloy. All tests, with the exception of the determination of wear, were made at 20, 60, 100, 150 and 200° C. (68, 140, 212, 300 and 390° F.). The resistance to wear was determined only at room temperature, approximately 20° C. (68° F.).

Simultaneously with the laboratory tests there was carried out a series of service tests of bearings made of some of the alloys which were installed in motors of U. S. Army trucks in service at Camp Holabird. The results of these service tests are reported in this paper.

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[1] J. R. Freeman, Jr., and R. W. Woodward, "Some Properties of White-Metal Bearing Alloys at Elevated Temperatures," U. S. Bureau of Standards *Technologic Paper No. 188* (1921).

[2] J. R. Freeman, Jr., and P. F. Brandt, "The Influence of the Ratio of Length to Diameter in the Compression Testing of Babbitt Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. 23, Part II, p. 150 (1923).

[3] O. W. Ellis and G. B. Karelitz, "A Study of Tin-Base Bearing Metals," *Transactions*, Am. Soc. Mechanical Engrs., Vol. 49–50, MSP 50-11, p. 13 (1927–1928).

[4] O. W. Ellis, "Note on Lead-Tin-Antimony Alloys," *Journal*, Inst. Metals, Vol. XIX, Part 1, p. 151 (1918).

[5] O. W. Ellis, "The Influence of Pouring Temperature and Mold Temperature on the Properties of a Lead-Base Anti-Friction Alloy," *Journal*, Inst. Metals, Vol. XXXIV, Part 2, p. 301 (1926).

[6] O. W. Ellis, "The Use of Lead in Mechanical Engineering Practice," *Transactions*, Am. Inst. Chemical Engrs., Vol. XX, p. 167 (1927).

[7] E. R. Darby, "Properties of Bearing Metals at Normal and Elevated Temperatures," Symposium on Effect of Temperature on the Properties of Metals, published jointly in the American Society for Testing Materials and The American Society of Mechanical Engineers, p. 316 (1931).

ALLOY COMPOSITIONS

Most of the alloys chosen for study corresponded to selected compositions appearing in the Society's Standard Specifications for White-Metal Bearing Alloys.[1] The alloys were chosen to give a reasonably wide range of compositions and to include those which find wide use in service. Virgin materials were used in the preparation of all alloys made at the Bureau. These materials[2] included Banca tin, and commercially pure lead, antimony, cadmium and zinc, and chemically pure (reagent grade) copper. The alkaline-earth metal hardened lead alloy was furnished in ingot form through the courtesy of the National Lead Co. This alloy is composed principally of lead which is hardened by the additions of alkaline-earth metals such as barium and calcium. This alloy will be referred to as "hardened lead." Chemical analyses of all the alloys were made and are reported in Table I.

TABLE I.—RESULTS OF CHEMICAL ANALYSES OF WHITE-METAL BEARING ALLOYS.

Alloy	Lead, per cent	Tin, per cent	Antimony, per cent	Copper, per cent	Cadmium, per cent	Zinc, per cent	Other Constituents, per cent
No. 1	....	90.9	4.6	4.5	....	....	....
No. 3	....	83.8	8.1	8.1	....	....	....
No. 6	62.3	20.8	15.5	1.4	....	....	....
No. 7	78.8	8.4	12.8	....	....	....	....
No. 8	79.7	5.0	15.3	....	....	....	....
No. 10	87.0	1.2	11.8	....	....	....	....
No. 11	88.1	....	11.9	....	....	....	....
Alkaline-earth metal hardened lead[a]	96.93	0.18	....	0.1	....	....	Hg, 0.33; Ba, 1.70; Ca, 0.70.
Cadmium-zinc[b]	....	....	....	....	82	18	....
A	80.6	3.8	13.5	1.0	0.2	....	Ni, 0.2; As, 0.6.

[a] Analysis made by the National Lead Co.
[b] Nominal composition.

APPARATUS AND TESTS

Resistance to Wear:

The wear tests were made on the Amsler machine, modified as shown in Fig. 1. In previous use of the Amsler machine at this Bureau,[3] the minimum load obtainable was 40 lb. The principal modifications which were necessary to adapt this machine to the testing of white metals consisted in adding the two springs, *S* and *S'* (Fig. 1) to reduce the load on the test specimens, and installing means for providing a continuous flow of kerosine on the specimens. The kerosine provided partial lubrication and also served to cool the specimens.

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[1] 1930 Book of A.S.T.M. Standards, Part I, p. 711.

[2] The tin, lead and antimony used in the preparation of these alloys were furnished through the courtesy of the National Lead Co.

[3] H. J. French, "Wear and Mechanical Tests of Some Railroad Bearing Bronzes," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 298 (1928).

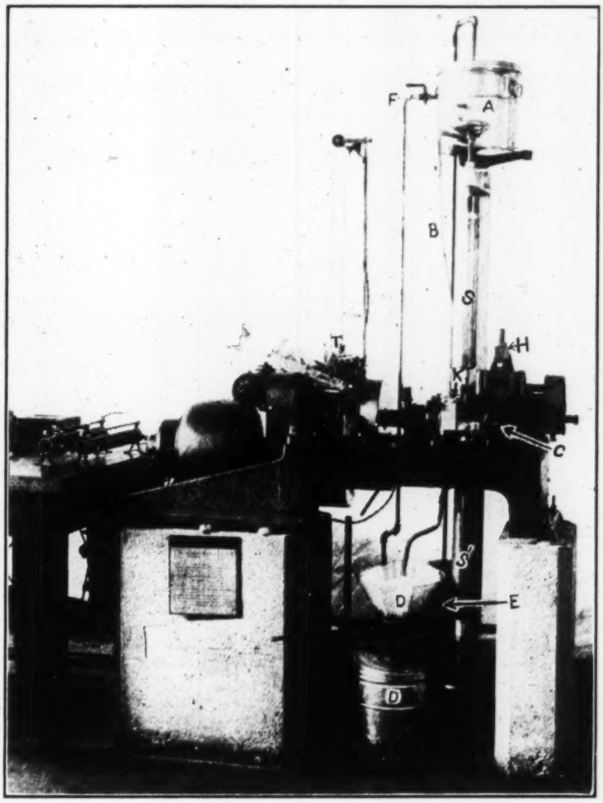

FIG. 1.—Amsler Machine for the Determination of Resistance to Wear.

K, Specimens (see Fig. 2 for detailed drawing).
T, Friction dynamometer.
S, Calibrated spring for adjusting pressures between test specimens.
S', Equalizing spring to offset weight of head *H*.
A, Reservoir for kerosine.
B, Pipe for transmitting kerosine to specimen.
D, Filter and reservoir for reclaiming kerosine.
E, Pump for returning reclaimed kerosine to reservoir *A* through pipe *E*.
F, Overflow for maintaining constant head of kerosine in *A*.

The specimens, shown in Fig. 2, consisted of a reference "A" made of S.A.E. 1045 steel, heat treated to give a Brinell hardness of about 240, and a test specimen "B" which consisted of a "tire" of white-metal bearing alloy cast on a bronze ring. A load of 5 lb. was placed on the steel specimen during test. A stream of kerosine was directed on the test specimen near its area of contact with the reference specimen.

Resistance to Pounding:

The apparatus used in the pounding tests was changed from the form in which it was used in previous work on bearing bronzes[1] by the substitution of a 2-lb. hammer for the 7-lb. hammer. The specimens were chill-cast cylinders, machined to 0.8 in. long by 0.4 in. in diameter (20 by 10 mm.). Each blow of the hammer (2-in. drop) was equivalent to approximately 0.33 ft-lb. energy input. Tests were made at 20, 60, 100, 150 and 200° C. (68, 140, 212, 300 and 390° F.). The deformation produced by a given number of blows was determined at increments up to 1000 blows.

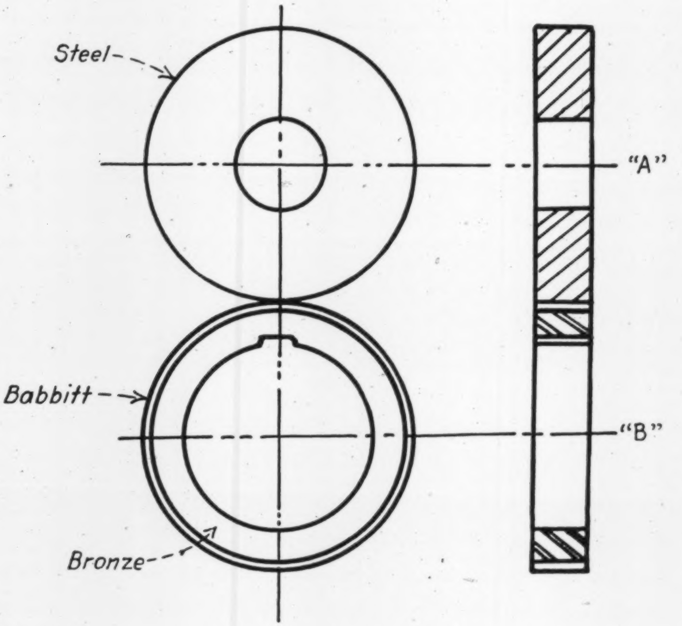

FIG. 2.—Diagram Showing Test Specimens as Set in the Amsler Wear Testing Machine.

Single-Blow Impact Value:

The Izod impact machine which was modified for tests at elevated temperatures and described in a previous Bureau report on bearing bronzes[1] was used for the single-blow impact tests. The test specimens were chill cast to within $\frac{1}{8}$ in. of their finished cross-sectional dimensions. Tests were carried out at the same temperatures as in the pounding tests.

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[1] H. J. French, "Wear and Mechanical Tests of Some Railroad Bearing Bronzes," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 298 (1928).

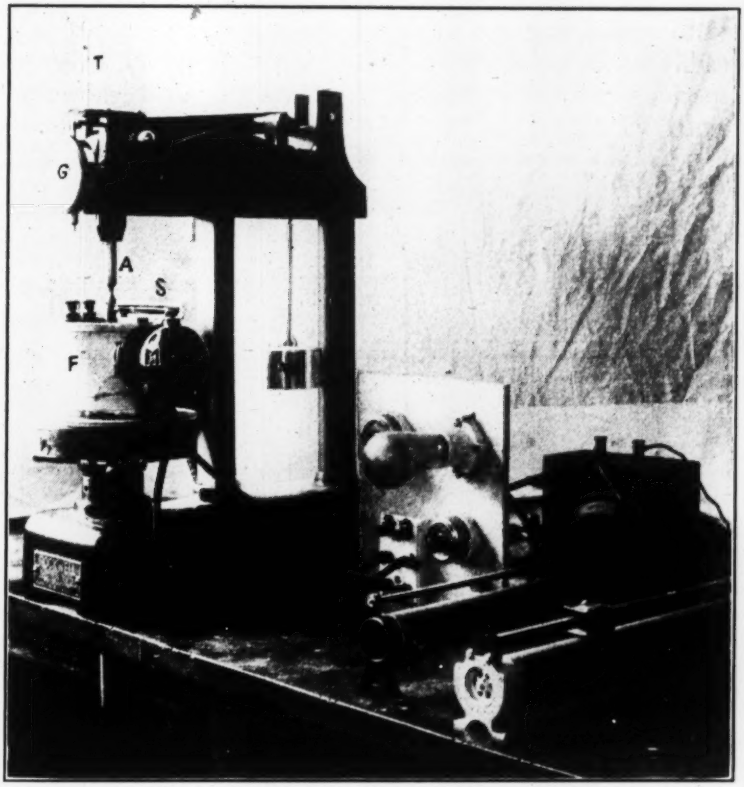

FIG. 3.—Rockwell Hardness Testing Machine.

A, Special adapter for 10-mm. ball.	*T*, Thermometer.
F, Heating bath for specimen.	*W*, Weight for applying load.
M, Motor for keeping glycerine in bath agitated to maintain uniform temperature.	*G*, Gage for obtaining Rockwell readings.
	S, Suction vent for removing fumes.

Hardness Number:

Brinell hardness numbers were determined with a Rockwell hardness testing machine equipped with a 10-mm. ball. The specimens were heated by means of a glycerin bath mounted on the platform of the Rockwell machine as shown in Fig. 3. Figure 4 shows details of the heating bath and the manner in which the specimen was supported for test. The test specimen was a chill-cast disk, 2 in. in diameter by $\frac{1}{2}$ in. thick. A 60-kg. load was used and the test temperatures were the same as those previously listed.

Compressive Strength:

A special strain gage, shown in Fig. 5, was designed[1] for measuring the deformation of specimens under compression at elevated temperature. The Ames dial, *D*, mounted on this apparatus was calibrated to read directly to 0.0005 in. and readings to 0.0001 in. could be readily estimated. The furnace could be slipped over bars *A* and specimen *C* by first removing the strain gage *D B* (shown in foreshortened view in Fig. 5). The strain gage when replaced was external to the furnace. In the strain gage, use was made of locally balanced constraints, *J*, *H*, and Ewing equalizing yokes, *B*, and flexure-plate hinges, *E*, *G*. Computations showed that the deformation of the compression heads *A* could not exceed 0.0003 in. per inch up to 9000 lb. per sq. in. stress on the specimen and was therefore negligible. Tests were made on a Riehle tension-compression testing machine of 10,000 lb. capacity. The cylindrical specimens, 1 in. by 0.505 in. in diameter, were machined from $\frac{5}{8}$-in. diameter chill-cast bars. The load was applied in increments of 50 lb., this increment being equivalent to an increase in stress of 250 lb. per sq. in. The tests were made at the various temperatures already listed.

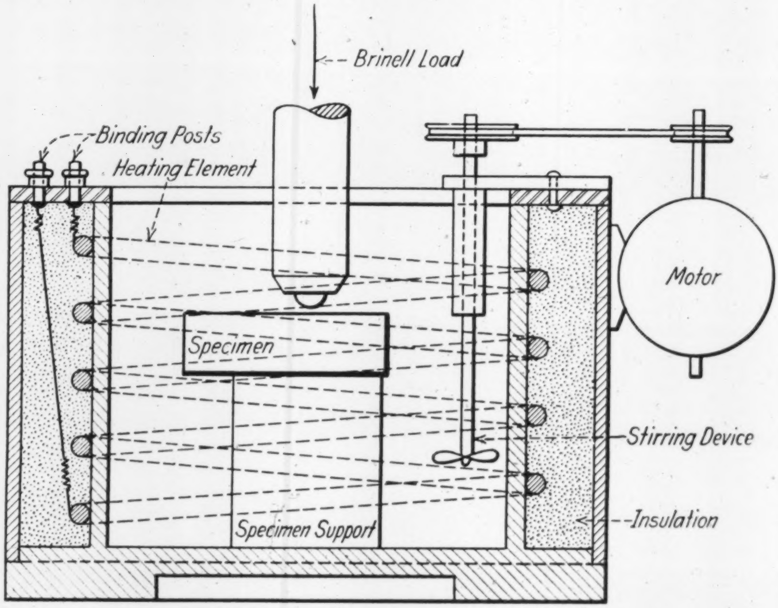

Fig. 4.—Heating Device Used with Rockwell Hardness Testing Machine in Determining Hardness at Elevated Temperatures.

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[1] The authors are indebted to L. B. Tuckerman of the U. S. Bureau of Standards for the design of the strain gage used.

Service Tests:

Two complete sets of babbitt-lined bronze crankshaft bearings were prepared[1] for service tests. Four different compositions were used for the liners, namely, alloy No. 1, "hardened lead," alloy No. 10, and an alloy of 90 per cent tin and 10 per cent copper which is frequently used in Army trucks. These bearings, which were all of the removable type, comprised two large main bearings, one small main bearing and four connecting-rod bearings in each set. Each bearing was first fitted into its proper position in one of the two motors and then removed before test for weighing and gaging. Each of the

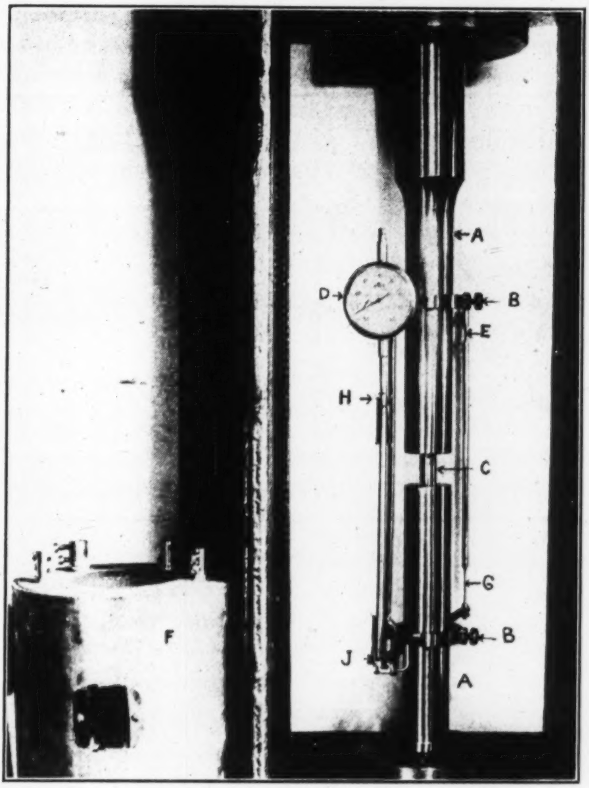

FIG. 5.—Apparatus for Measuring Deformation of Specimens Under Compressive Stresses.

A, Compression adapters.
B, Yokes for holding apparatus on adapters.
C, Specimen.
J, *H*, Locally balanced constraints.
D, Strain gage.
F, Furnace for use when testing specimens at elevated temperatures.
E, *G*, Flexure plates.

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[1] These bearings were furnished through the courtesy of the Bohn Aluminum and Bronze Co.

four compositions was represented in each motor. The motors were then placed in service in two class B Army trucks. Records were kept of the daily mileage of each truck and of the hours of operation and number of revolutions of the crankshaft of each motor. In the latter stages of the service tests, the motors were idled for portions of the time when the trucks were not in road service in order to shorten the time required to produce appreciable wear in the bearings under test. The quantity of oil was at all times maintained within 2 quarts of the 12-quart capacity of the crankcase.

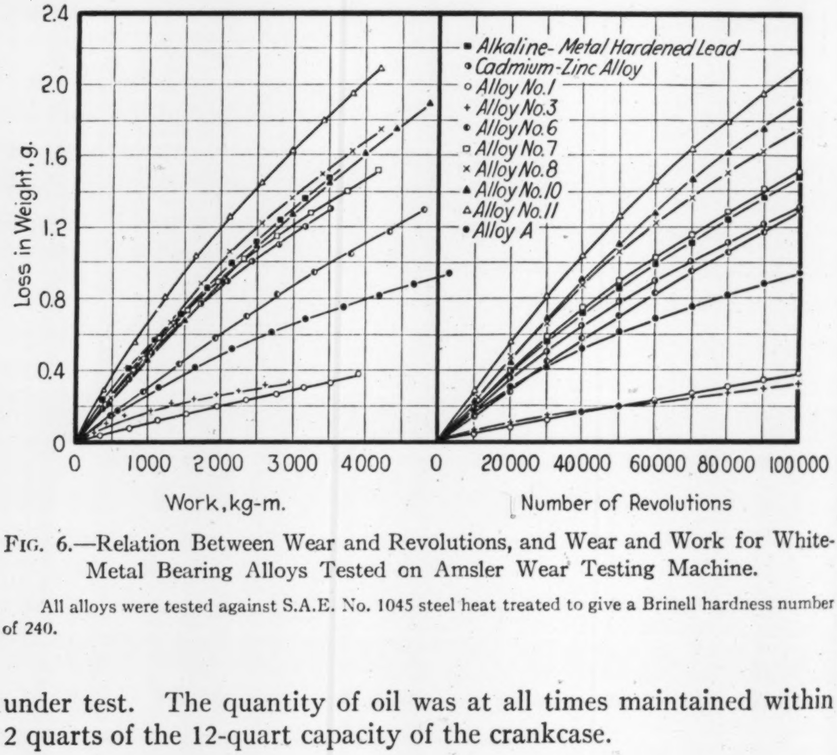

FIG. 6.—Relation Between Wear and Revolutions, and Wear and Work for White-Metal Bearing Alloys Tested on Amsler Wear Testing Machine.

All alloys were tested against S.A.E. No. 1045 steel heat treated to give a Brinell hardness number of 240.

RESULTS AND DISCUSSION

Resistance to Wear:

Preliminary wear tests on the white-metal bearing alloys made without any liquid coolants or lubricants resulted in considerable "flat-wheeling" of the specimens which caused "bumping" and increased friction. It was also exceedingly difficult to obtain check results on any given material. The use of kerosine, supplied continuously to the test specimens during test, eliminated these difficulties. The kerosine also produced a condition of partial lubrication. Complete lubrication would have been undesirable since such a condition has been found to reduce the amount of wear to a negligible quantity.[1]

Figure 6 shows the results obtained in the wear tests. These results clearly indicate that the wear rates of the tin-base alloys were considerably less than those of the lead-base and cadmium-zinc alloys. These results are substantially in accordance with those reported by Rolfe[2] who found that tin-base bearing metals were superior to lead-base alloys in resistance to wear at various temperatures. Figure 6 also shows the general effect of different percentages of tin in the lead-antimony-tin alloys. Thus, a lead-antimony alloy containing no tin showed an approximate loss of 0.2 g. per 10,000 revolutions while this loss was about 0.1 g. for the alloy containing 20 per cent tin. Alloys containing intermediate amounts of tin showed corresponding rates of wear between 0.1 and 0.2 g. per 10,000 revolutions. The lead-base alloy *A*, which contained antimony, cadmium, nickel, tin, copper and arsenic, was found to have higher resistance to wear than the other lead-base alloys tested.

The work-wear curves likewise show a marked difference between the lead-antimony alloy containing 20 per cent tin and the alloy containing no tin. Only slight differences were noted between the alloys containing 1, 5 and 8 per cent tin. However, taken together they lie between the alloys containing no tin and 20 per cent tin, respectively. The "hardened lead" showed about the same ratio of wear to work done as did the lead-base alloys containing 1 to 8 per cent tin. The same was true of the cadmium-zinc alloy. Alloy A showed a lower ratio of wear to work than did any of the lead-base alloys. There was a considerably lower rate of wear for a given amount of work with the tin-base alloys than with any of the other materials tested. The rates were about the same, however, for both tin-base alloys used.

Resistance to Pounding:

The results of the pounding tests, Fig. 7, show the relation at different temperatures of the number of blows of the hammer to the resulting deformation. Differences in deformation of 0.5 per cent were considered as negligible, since on the basis of a babbitt lining $\frac{1}{16}$ in. thick, this would be equivalent to only about 0.0003 in.

The "hardened lead" and the cadmium-zinc alloy showed unusually high resistance to deformation at all temperatures. It is

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[1] H. J. French, "Wear and Mechanical Tests of Some Railroad Bearing Bronzes," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 298 (1928).

[2] R. T. Rolfe, "Bearing Alloys," *Proceedings*, Manchester Assn., England, October, 1929. Discussion reported in *The Metallurgist* (Supplement to *The Engineer*), January 31, 1930, p. 9.

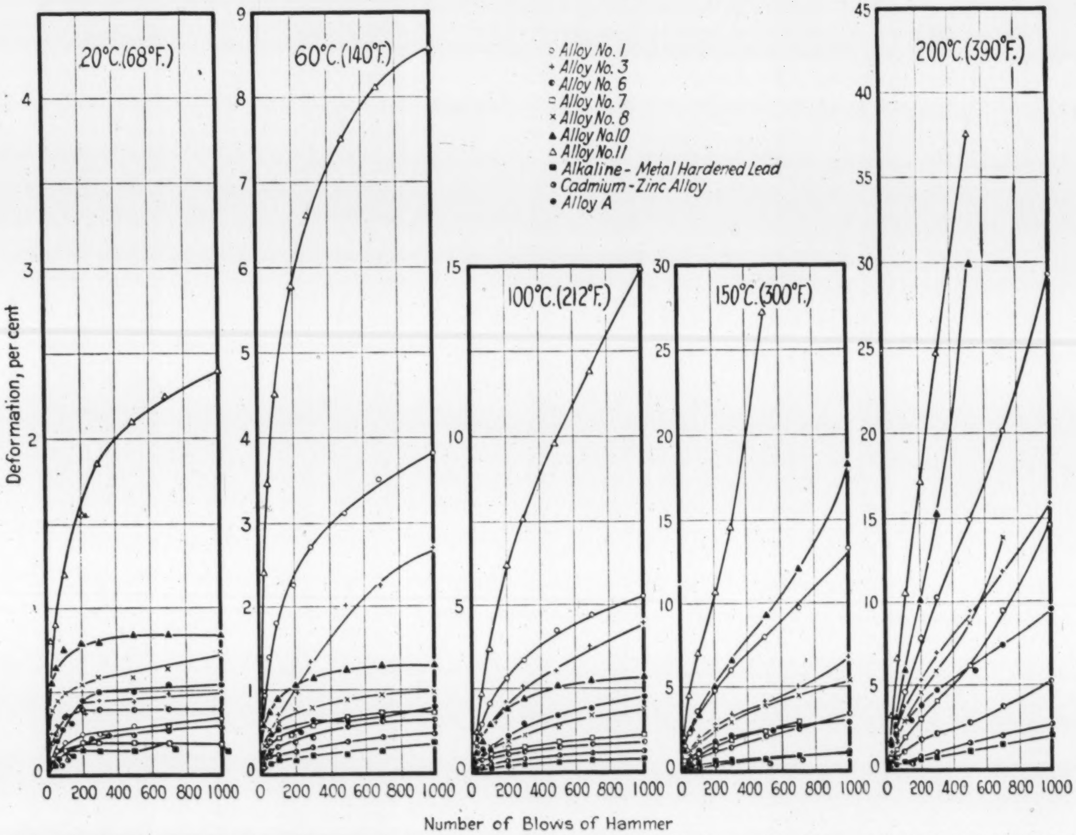

Fig. 7.—Relation of Deformation to Number of Blows of Hammer at Different Temperatures in Pounding Tests.

Energy absorbed by specimens for each blow of hammer was approximately 0.33 ft-lb.

noteworthy that the tin-base alloy, No. 1, which at room temperature showed the same degree of resistance to deformation as the other alloys, weakened rapidly as the temperature was increased. Tin-base alloy No. 3 showed a similar effect but it was not so marked. In general, an increase in the tin content of the lead-base alloys resulted in greater resistance to deformation. Lead-base alloy *A* which contained only 3.8 per cent tin was markedly better at the higher temperatures than the antimony-lead alloys which contained up to 10 per cent tin.

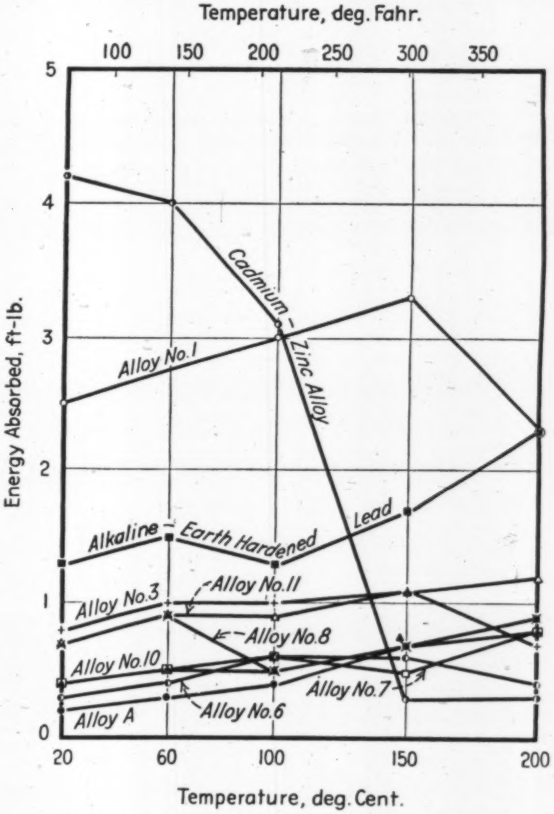

FIG. 8.—Effect of Temperature upon the Impact Resistance (Izod Test) of White-Metal Bearing Alloys.

Single-Blow Impact Value:

The results of the Izod impact tests are shown in Fig. 8. Each plotted point represents an average of five determinations, each made on a different specimen. The cadmium-zinc alloy of eutectic com-

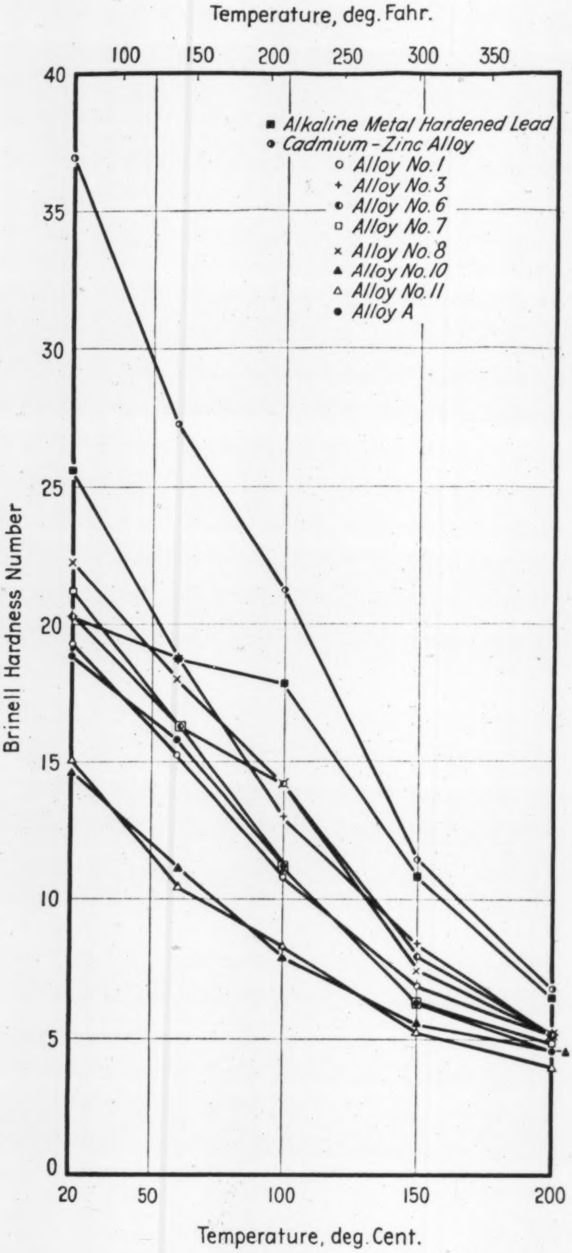

FIG. 9.—Brinnel Hardness of White-Metal Bearing Alloys at Different Temperatures.

position exhibited a relatively high impact resistance up to 100° C. (212° F.) which decreased very markedly at temperatures in excess of 100° C. Aside from the cadmium-zinc alloy, tin-base alloy No. 1 showed higher resistance to impact than did the other alloys; it even equalled the cadmium-zinc alloy at 100° C. (212° F.) and exceeded it at higher temperatures. The "hardened lead" showed a general increase in resistance to impact as the temperature of test was increased and at 200° C. (390° F.) was equal to tin-base alloy No. 1. The lead-base alloy containing no tin (alloy No. 11) was superior to those containing tin, and closely approached the values obtained for tin-base alloy No. 3. In general, the impact values of the lead-base alloys decreased as the tin content increased. The results obtained for the lead-base alloys excepting those for the "hardened lead" fell within a very narrow range and to all intents and purposes may be said to have the same impact resistance at any given temperature.

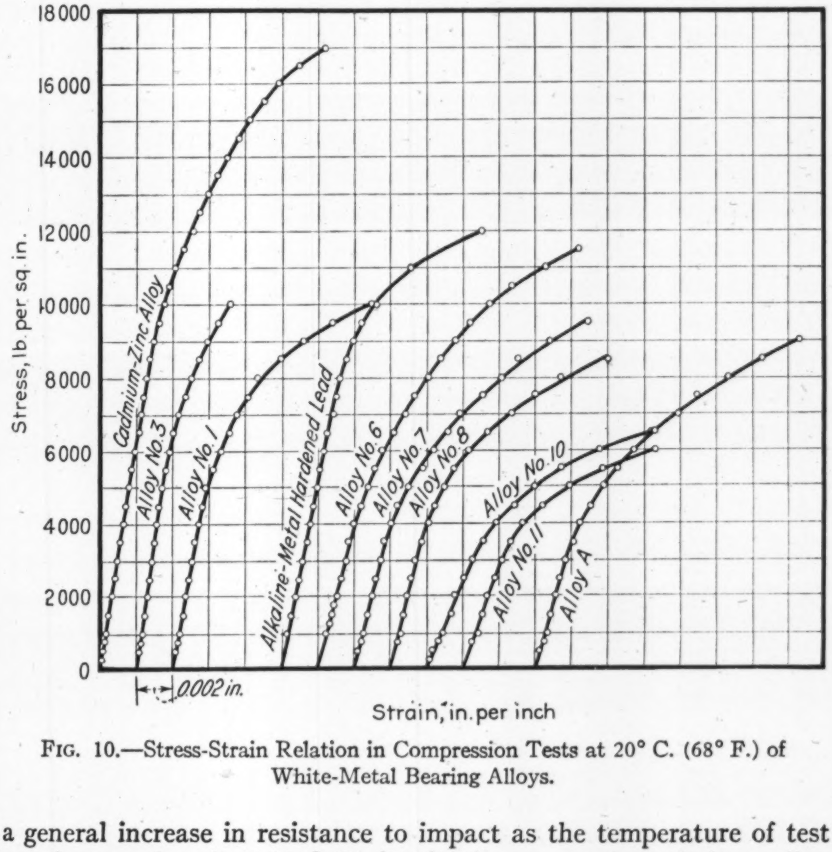

FIG. 10.—Stress-Strain Relation in Compression Tests at 20° C. (68° F.) of White-Metal Bearing Alloys.

Hardness Number:

The results of the Brinell hardness tests are shown graphically in Fig. 9. These correspond very closely to the results of previous Bureau tests[1] on the hardness at 20 and 100° C. (68 and 212° F.) of the white-metal bearing alloys of the Society's tentative specifications. Figure 9 shows a marked decrease in hardness of all the alloys as the temperature was increased, particularly above 100° C. (212° F.). The cadmium-zinc alloy which was considerably harder than the "hardened lead" at 20° C. (68° F.) and 60° C. (140° F.) showed much less superiority in this property at higher temperatures.

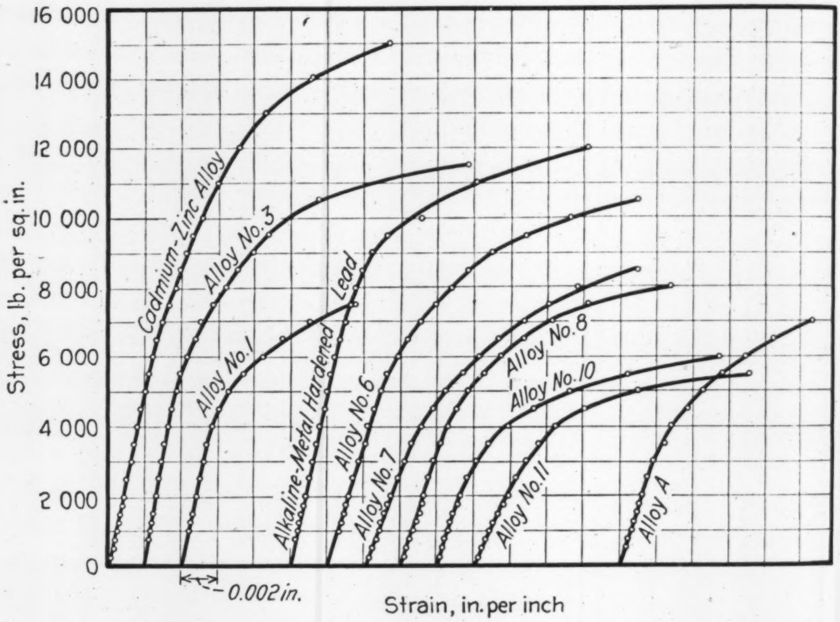

FIG. 11.—Stress-Strain Relation in Compression Tests at 60° C. (140° F.) of White-Metal Bearing Alloys.

Compressive Strength:

The stress-strain relationships in compression for each of the test temperatures are shown in Figs. 10 to 14. By using the least count of the extensometer as the criterion for the "departure from a straight line,"[2] it was possible to determine approximately the limits

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[1] J. R. Freeman, Jr., "The Physical Properties of the A.S.T.M. Tentative Standard White Metal Bearing Alloys," *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part I, p. 207 (1922).

[2] Discussion by L. B. Tuckerman of paper by R. L. Templin, "The Determination and Significance of the Proportional Limit in the Testing of Materials," *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part II, p. 538 (1929).

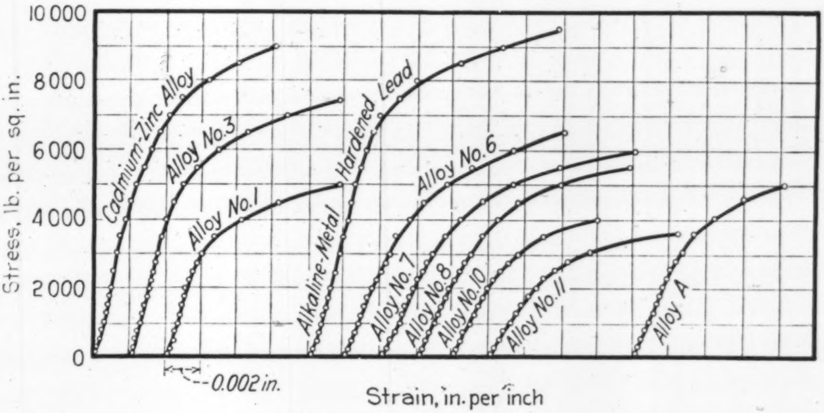

FIG. 12.—Stress-Strain Relation in Compression Tests at 100° C. (212° F.) of White-Metal Bearing Alloys.

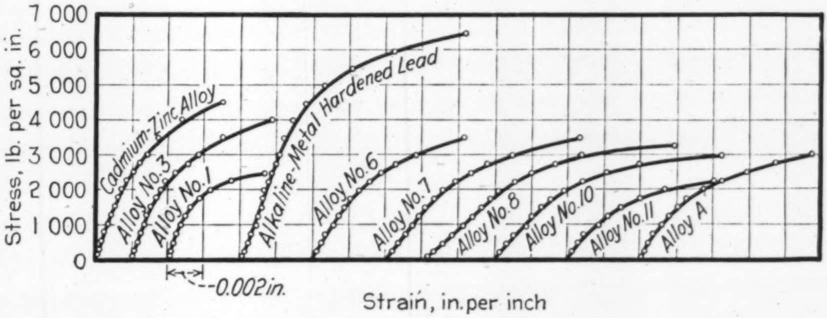

FIG. 13.—Stress-Strain Relation in Compression Tests at 150° C. (300° F.) of White-Metal Bearing Alloys.

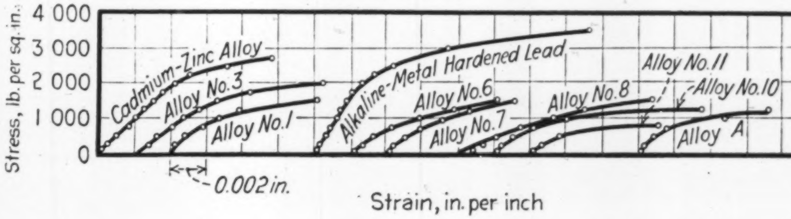

FIG. 14.—Stress-Strain Relation in Compression Tests at 200° C. (390° F.) of White-Metal Bearing Alloys.

of proportionality of stress and strain for most of the alloys tested at room temperature (Fig. 10). It became increasingly difficult and questionable, however, to determine this limit of proportionality as the temperature of test increased. Hence, in order to show graphically the effect of temperature on any given alloy, there was selected an arbitrary value for the strain, namely, 0.3 per cent, which may be considered to represent the relative proportional limits. The stresses necessary to produce deformations of 0.3 per cent as determined from Figs. 10 to 14 were plotted against the corresponding temperatures as shown in Fig. 15. This figure indicates that the "hardened lead" was capable of sustaining higher stresses at temperatures above 60° C. (140° F.) than were the other alloys. The cadmium-zinc and the two tin-base alloys fell off very markedly in their load-carrying ability as the temperature was increased. The lead-base alloys, with the exception of the "hardened lead," showed very distinct differences in resistance to deformation under compressive stresses at room temperature. These differences, however, decreased with increased temperature of test until at 200° C. (390° F.) they were negligible.

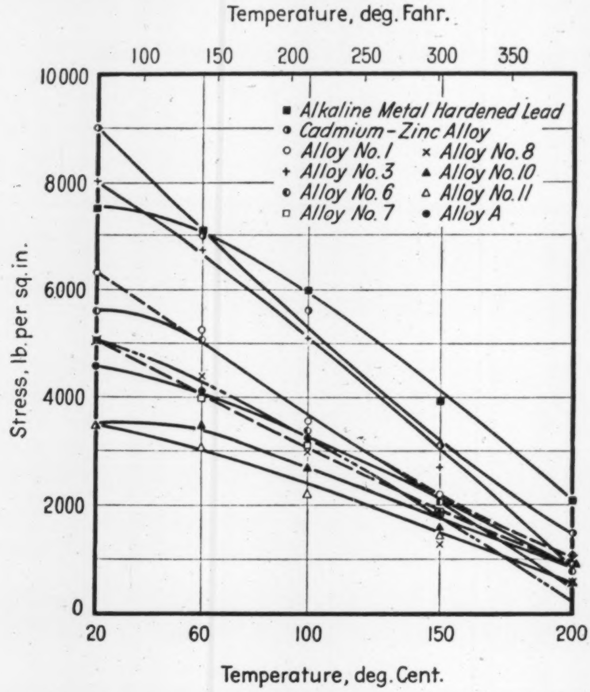

FIG. 15.—Relation of Compression Stress, Producing 0.3 per cent Deformation, to Temperature of Test.

Service Tests:

Compositions of the white-metal alloys used in the service test bearings are listed in Table II. The first inspection of the bearings was made after the two motors had run for 170 hours at an average speed of 660 r.p.m. and 173 hours at an average speed of 770 r.p.m., respectively. This was equivalent to approximately 1200 and 1700 miles of travel of the trucks, respectively. This period has been arbitrarily designated as the "wearing-in" period. The thickness of each bearing was accurately measured and from these measurements the increase in inside diameter of the bearing was determined. The bearings were also weighed and then reinstalled in the motors for further test. The second period of the test has been designated as the "test" period. It consisted of 865 hours running of one motor at an average speed of 630 r.p.m. and of 823 hours running of the other motor at an average speed of 700 r.p.m., equivalent to approximately 6000 miles of travel for each test truck. The bearings were then again removed for measuring and weighing. The losses suffered by these bearings in service for both periods are given in Table II under the headings of "wearing-in" period and "test" period, respectively. The increases in inside diameter for the "test" period only are reported (Table II). The data from the "test" period are undoubtedly the more reliable, since the condition

TABLE II.—SERVICE TESTS OF WHITE-METAL BEARING ALLOYS IN CLASS B ARMY TRUCKS.

Bearing Designation	Composition, per cent						Location of Bearing on Crankshaft	Weight Loss, g.		Increase in Inside Diameter of Bearing, in., "final-test" period	
	Tin	Lead	Copper	Antimony	Barium	Calcium		"Wearing-in" Period	"Test" Period		
A-1[a]	90.48	0.58	4.26	4.69	....	....	Connecting rod; No. 2	2.4	1.32	0.0012	Truck No. 105: "Wearing-in" period, 170 hours; average speed, 660 r.p.m. "Test" period, 865 hours; average speed, 630 r.p.m.
A-2	....	....	....	....	....	....	Rear-main	1.38	1.41	0.0010	
B-1[b]	90.0	....	10.0	....	....	....	Connecting rod; No. 1	1.28	1.72	0.0019	
C-1[a]	3.27	82.52	0.15	14.05	....	....	Connecting rod; No. 3	2.59	2.69	0.0023	
C-2	....	....	....	....	....	....	Center-main	1.86	2.53	0.0021	
D-1[b]	....	97.5	....	....	1.75	0.75	Connecting rod; No. 4	3.88	[c]	[c]	
D-2	....	....	....	....	....	....	Small-main	8.63	5.30	0.0036	
A-3[a]	90.48	0.58	4.26	4.69	....	....	Connecting rod; No. 3	1.05	0.64	0.0012	Truck No. 106: "Wearing-in" period, 173 hours; average speed, 770 r.p.m. "Test" period, 823 hours; average speed, 700 r.p.m.
A-4	....	....	....	....	....	....	Small-main	0.5	0.64	0.0010	
B-2[b]	90.0	....	10.0	....	....	....	Connecting rod; No. 4	0.69	[c]	[c]	
C-3[a]	3.27	82.52	0.15	14.05	....	....	Connecting rod; No. 1	1.73	1.32	0.0014	
C-4	....	....	....	....	....	....	Rear-main	1.98	0.81	0.0011	
D-3[b]	....	97.5	....	....	1.75	0.75	Connecting rod; No. 2	3.07	2.06	0.0019	
D-4	....	....	....	....	....	....	Center-main	3.28	2.06	.00017	

[a] Analyses by the Bohn Aluminum and Bronze Co.

[b] Compositions are nominal values and not by analysis.

[c] Bearings were damaged while being transported to Camp Holabird for reinstallation in motors for "test" period.

of the machined surfaces of the bearings would very seriously modify both increases in diameter and losses in weight during the "wearing-in" period.

The bearings which contained 90.48 per cent tin, 4.26 per cent copper and 4.69 per cent antimony (Table II) and correspond very closely in composition to alloy No. 1 (Table I), showed less wear than any of the other bearings made of different alloys. The bearings made of 90 per cent tin and 10 per cent copper were next in order of wear resistance. The "hardened lead" showed the greatest wear of the four alloys tested. The lead-antimony-tin bearing alloy contained 3.27 per cent tin (Table II) and corresponded most nearly to alloy No. 8 (Table I). The bearings made with this material showed lower resistance to wear than the tin-base bearings, but higher resistance than the "hardened lead."

Table II shows that the bearings in the motor of truck No. 105 suffered greater wear than those in the motor of truck No. 106, in spite of the fact that the former motor ran 3 hours and more than 100 r.p.m. (approximately 500 miles) less than the latter. It is obviously quite possible that exactly similar surface finishes did not obtain on the crankshaft surfaces in contact with the bearings in the two motors. It is likewise possible that the clearance between the bearings and shafts was different in the two motors. It is noteworthy, however, that the order of wear-resistance for the several bearing metal compositions used was the same for each motor.

A comparison of the results of these tests with those reported for the laboratory wear tests (Fig. 6) shows that the tin-base alloy containing about 91 per cent tin, 4.5 per cent copper and 4.5 per cent antimony was superior, with respect to loss in weight in wear, to the "hardened lead" and the lead-antimony-tin alloys in both the service tests and the laboratory tests.

CONCLUSIONS

The following conclusions are drawn:

1. No one of the bearing alloys used was found to excel in all of the mechanical properties which are believed to indicate suitability of a bearing metal for service.

2. The tin-base bearing alloys showed a lower wear-rate at 20° C. (68° F.) and in most cases had higher single-blow impact resistance at temperatures between 20 and 200° C. (68 and 390° F.) than the lead-base and the cadmium-zinc alloys. In most cases, the tin-base alloys showed lower resistance to pounding at temperatures up to 200° C. (390° F.) than the other alloys, the most notable exceptions

being the lead-antimony alloys containing less than 5 per cent tin. The hardness and compressive properties of the tin-base alloys were lower than those of the "hardened lead" and the cadmium-zinc alloys.

3. The lead-antimony-tin alloys showed in most cases higher mechanical properties as the tin content was increased.

4. The results indicate that the alkaline metal hardened lead and the cadmium-zinc alloys had higher hardness, greater resistance to deformation under pounding and better compression properties at temperatures up to 200° C. (390° F.) than the tin-base and lead-antimony alloys.

5. The results obtained in the service tests showed that the tin-base alloys were superior in their wear resistance to both the "hardened lead," and lead-antimony-tin alloy containing about 3 per cent tin. These results were consistent with the laboratory results on wear.

Acknowledgments:

The authors are indebted to R. L. Dowdell, formerly head of the Division of Metallurgy of the U. S. Bureau of Standards, W. A. Cowan, Assistant Chief Chemist of the National Lead Co., and Verne Skillman, Chief Metallurgist of the Bohn Aluminum and Bronze Co. for their many valuable suggestions and aid in the course of this investigation. Particular acknowledgment is made to The Bunting Brass and Bronze Co. for the assistance rendered in the laboratory work by C. C. Tudor, Research Assistant at the Bureau.

DISCUSSION

MR. O. W. ELLIS[1] (*presented in written form*).—The work which the authors have conducted on the resistance to pounding of the various white metals investigated is of particular interest to the writer, since he made a very complete inquiry into the resistance to pounding of the tin-base bearing metals, which were the subject of the paper by himself and Mr. G. B. Karelitz referred to on page 537 of the authors' paper. The results of these pounding tests were not considered of sufficient importance to warrant inclusion in the above paper. In the first place, the equipment which was employed in carrying out these tests was not sufficiently rigid to make it possible to state with perfect confidence that the results would be reproducible, were the apparatus to be used for the same experiments at a later date. One thing was noted, however, which may be of interest, namely, the deformations produced by a definite number of blows were related in a very simple manner to the Brinell hardness numbers of the alloys investigated. The relationship was of such a character as to enable one to say that, knowing the Brinell hardness number of any alloy containing tin, antimony, and copper (within the limits covered by the experiments), one could arrive at the percentage deformation resulting from a certain, definite number of blows. The writer is sorry that he is unable to present graphically the results of the tests which were conducted by him in this connection, as they are no longer in his possession.

Turning to the question of the Brinell hardness of the various white-metal bearing alloys which were tested by the authors, one is surprised at the low value shown for alloy No. 3 in Fig. 9. The writer would have expected this alloy to have a Brinell hardness of at least 27 at room temperature (compare Fig. 40 of the Ellis and Karelitz paper). In this connection it may be worthy of note that a very close estimate can be made of the compression strength producing 0.3 per cent deformation for alloys Nos. 1 and 3 at different temperatures (see Fig. 15 of the authors' paper) by using the hardness numbers shown in Fig. 9 and the curve showing the relationship between yield point and hardness of the tin-antimony-copper alloy given in Fig. 54 of the Ellis and Karelitz paper. This finding serves, it is felt, to support the view that the relationships shown in Figs.

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52, 53, and 54 of that paper can be applied somewhat more widely than these workers supposed.

The authors' first conclusion is, I believe, one of the most important that they could have put forward. It agrees very fully with the view which the writer has himself expressed, and which Mr. G. B. Karelitz at the time of the writer's association with him would have likewise put forward. The metallurgist who is asked what is the best white-metal bearing alloy is most certainly placed in a difficult position. That some costly alloys are being used where cheaper ones could well be employed is certainly true. With our present knowledge, however, it is difficult to state beforehand what mixture is likely to give the best service. Particularly is this the case when the metallurgist has to contend with such variables as are introduced into the picture by the mechanical engineer.

MR. F. O. CLEMENTS.[1]—We, in the automobile industry, test bearings under very extreme conditions, for our troubles are largely related to the higher oil temperatures. Almost any kind of a bearing will stand up indefinitely with low loadings and idling speeds. Silver and tin as bearings materials give an excellent account of themselves, if the temperatures remain low. The wear factor is almost negligible. The automobile, however, is oftentimes called upon to deliver its full horsepower output for long intervals of time. The regular babbitt materials of the better grades give a fairly good account of themselves under these severe driving conditions. We are, however, close to the melting point of the Babbitt metal and we also recognize that bearings lose much of their ability to withstand the loads involved at these elevated temperatures. The question of a good bond is of the utmost importance. So this whole question of creep measurements at extreme temperature is the crux of the bearing situation. We will need, as duties increase, higher melting point linings for bearings with higher factors of safety. So this paper presents data of considerable moment on a subject of great importance.

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[1] Technical Director, Research Laboratories, General Motors Corp., Detroit, Mich.

METHOD OF PREPARATION OF LEAD AND LEAD ALLOY CABLE SHEATH FOR MICROSCOPIC EXAMINATION

By W. H. Bassett, Jr.,[1] and C. J. Snyder[2]

Synopsis

Lead and lead alloy cable sheaths contain irregularities in grain structure that are best examined microscopically. Careful preparation of sheath samples is necessary because the grain structure of lead is very sensitive to "working." The microtome has been recommended for cutting a smooth surface but the authors obtain satisfactory results by filing and polishing. All polishing is done by hand with a circular motion on emery paper and broadcloth backed by plate glass. Gasoline is used as a lubricant and cleaning medium.

Lead and lead alloys require different etching reagents. A table of reagents used by various authorities is given. The authors recommend etching solutions for lead, lead-tin and lead-antimony alloys. In all cases specimens must have sufficient etching to remove the surface layer of fine grains developed by cutting or polishing.

Examination of structures with vertical light is recommended. Suitable magnifications for lead are 5 to 75 diameters, for lead-tin alloys 20 to 200 diameters, and for lead-antimony alloys 50 to 500 diameters.

Photographs demonstrating the results obtained are included.

Insulated electric power cables and telephone cables are usually covered with a coating of lead to protect the insulation from air, moisture and mechanical injury. Occasionally an alloy of lead with tin, antimony, calcium or cadmium is used. This sheath is extruded tightly and continuously over the cable. Like all manufactured products cable sheaths are subject to various characteristic imperfections such as blisters, laminations and oxide inclusions which frequently are not of sufficient magnitude to be visible without the aid of the microscope. Cable sheaths also contain one or two longitudinal welds extending the entire length of the sheath, which are best examined microscopically. It, therefore, has been necessary to adopt a suitable method of preparation of cable sheath specimens for microscopic examination which will clearly reveal the grain structure of the metal and its irregularities.

An examination consists roughly speaking of three steps, namely, the preparation including the cutting and the polishing of the specimen, the etching or treating in a suitable manner to make the structure visible, and the microscopy and photography.

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[2] Assistant Metallurgist, Anaconda Wire and Cable Co., Hastings-on-Hudson, N. Y.

The grain structure of lead is extremely sensitive to working of any sort, such as bending, hammering, stretching or any treatment that causes deformation of the metal. Even the weight of a lead tube pressing against a roller conveyor is sufficient to cause structural changes in the metal of the area immediately affected. Therefore, when the structure of a given piece of cable sheath is to be examined, it is necessary to prepare the micro specimen without deforming it in any manner. In other cases when defects only are to be examined such care is not necessary. The investigator can often obtain considerable information regarding the past history of a cable sheath by examining the full cross-section. If just a small piece of lead is taken for the microscopic examination, the irregularities which are present in the section of the lead cable sheath may be entirely overlooked. A sharp hacksaw with a wide "set" is satisfactory for taking a sample.

PREPARATION AND POLISHING

The preparation of the surface to be examined may be accomplished in one of several ways. F. F. Lucas recommends a microtome for cutting the surface smooth.(1)[1] The use of a special machine of solid construction is advised, the knives of which must be expertly sharpened. Such a machine produces excellent results and saves much time in preparing certain kinds of samples, but it is expensive. In recent communications to Subcommittee I on Selection and Preparation of Samples of the Society's Committee E-4 on Metallography, both R. S. Dean and H. A. Anderson have stated that when the expense of a special microtome is not permissible, a cheaper machine of light construction can be successfully used. Other authorities have employed a sharp chisel, plane, or draw knife for shaving the surface to be etched.

In the absence of a good microtome or in instances where the size or shape of a specimen is not suitable for microtome cutting, the following method of preparation will produce satisfactory results. The surface to be examined is smoothed off and made flat by rubbing it lightly over a stationary file of medium fineness. A 12-in. smooth milled Nicholson file has been used. The file must be kept clean and sharp so that it cuts and does not drag.

All polishing is done by hand with a circular motion on emery paper or broadcloth backed by plate glass. The paper or broadcloth should be kept well lubricated with an excess of gasoline, which, besides lubricating and cooling the specimen, floats away the lead particles removed by the abrasive and keeps both the emery and the specimen clean. Coarse emery should not be used as the grains become embedded in the metal and leave pits after etching. A long polish on Hubert's French emery paper No. 0 and a short polish on No. 000 or No. 0000 is often found satisfactory after careful filing when examination is to be made at 7 diameters or less. Very little pressure should be exerted. Polishing on each paper should be continued until the paper has been worn smooth, thus having the effect of a much finer paper. It is recommended, however, that an additional short polish be given using tripoli on broadcloth. When clean and ready to etch, the surface will have a gray satin finish

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[1] The boldface numbers in parentheses refer to the reports and papers given in the list of references appended to this paper, see p. 568.

TABLE I.—ETCHING REAGENTS FOR LEAD AND LEAD ALLOYS.

Reagent	Proportions, parts by volume						Specific Use	Authority
	Acetic[a]	Nitric[b]	Water	Glycerol	9-per-cent Peroxide	30-per-cent Peroxide		
Dilute nitric-acetic acids	3	4	16	—	—	—	Commercial lead Lead-tin alloys up to 3-per-cent tin	Authors Authors
Electrolytic etch with 60 per cent perchloric acid solution	—	—	—	—	—	—	Lead-tin alloys up to 3-per-cent tin Fair for commercial lead	Authors Authors
Nitric-acetic acid solution in glycerol	1	1	—	4	—	—	For lead For lead-antimony alloys	Vilella and Beregekoff (2) Vilella and Beregekoff (2)
	1	1	—	8	—	—	For lead-tin alloys	Vilella and Beregekoff (2)
Solution *A*, 50 per cent acetic acid plus peroxide	3	—	—	—	1	—	Lead-antimony alloys up to 2-per-cent antimony.	Authors
Solution *B*, to follow solution *A* for cleaning	1	—	—	—	3	—		
Acetic acid-peroxide solution, clean with nitric acid, if necessary	3	—	—	—	1	—	Lead-antimony alloys up to 2-per-cent antimony. Lead Lead-tin alloys Fair for lead and lead-tin alloys	Rutherford (4) Dean, Zickrick and Nix (5) Rutherford (4) Rutherford (4) Authors
Acetic acid-peroxide solution, clean with concentrated sodium hydroxide solution	3	—	—	—	—	1	Lead-antimony alloys Lead-calcium alloys	Anderson (see text) Anderson (see text)
Reagent No. 6 followed by 2-per-cent solution of acetic acid in alcohol, expose specimen while wet to air until sufficiently "stained"	—	—	—	—	—	—	For structural detail in lead-calcium alloys	Anderson (see text)

[a] Glacial acetic except where noted.

[b] Nitric acid 1.42 specific gravity.

with no visible scratches. The use of the usual polishing wheel has been found undesirable.

References to polishing of lead specimens for micro examination, as contrasted with cutting, have appeared in articles by Vilella and Beregekoff(2) and by Hodge and Heyer(3) but their procedures differ from that just given in a number of details.

ETCHING

When etching lead and lead alloy samples it must be borne in mind that the polished or cut surface consists of a layer of fine grains developed by the cutting and polishing. These fine grains must be removed before the true structure is disclosed. When the specimen during preparation has been too severely worked it may be badly pitted before this fine grain structure is entirely removed. In such a case another polish on No. 0000 emery and a repolish on the broadcloth with tripoli is required, after which a regular etch should be satisfactory.

A number of suggested etching reagents have been investigated and the ones given in Table I are those recommended by various authorities.

A mixture of glacial acetic acid and 9-per-cent peroxide was recommended by Rutherford(4) for etching lead and lead alloys and later by Dean, Zickrick and Nix(5) for etching lead-antimony alloys containing less than 2 per cent of antimony.

In a recent communication to the Society's Committee E-4, Mr. H. A. Anderson reported that through the cooperation of the Bell Telephone Laboratories and the Western Electric Co. a mixture of 30 per cent peroxide and glacial acetic acid in varying proportions had been produced which gave a desirable etch for lead-antimony and lead-calcium alloys. He added that staining on antimony alloys could be removed by swabbing with concentrated sodium hydroxide solution. For structural details in calcium alloys he recommended an additional treatment wherein the specimen is transferred directly from the etching bath into a 2 per cent solution of acetic acid in alcohol, exposing to the air until the desired amount of staining takes place. For microscopic examination, particularly for fine detail at considerable magnification, he stated that the etched specimen should be rinsed with alcohol or water and dipped in a 50 per cent solution of concentrated nitric acid. Final rinsing is with alcohol.

A solution of nitric and acetic acids in glycerol was recommended by Vilella and Beregekoff for lead and lead alloys(2).

Etching Commercial Lead:

After experimenting with various suggested etching reagents the authors found it advantageous to use different reagents for lead and its alloys. A warm, dilute solution of nitric and acetic acids produced the best results on lead and was also suitable for lead-tin alloys up to 3 per cent of tin. The solution is made up of 10 cc. nitric acid (sp. gr. 1.42) 7.5 cc. glacial acetic acid and 40 cc. of water, or proportional amounts to make the quantity desired, and should be freshly mixed for each specimen. It is used at 40 to 42° C. (104 to 108° F.) and the specimen is immersed in the solution for approximately twenty minutes, or until the fine grain structure and scratches are etched away. It is advisable to remove the specimen and swab the surface lightly with cotton in a stream of water several times during the twenty minutes. It is then finished by swabbing with clean, wet cotton, washed thoroughly in running water and quickly dried on a clean blotter to prevent tarnish.

The structure now disclosed may be satisfactory for ordinary examination at low powers, but much additional detail and sharpness of grain boundaries can be brought out by a short light polish on the broadcloth previously used and re-etching for from two to five minutes. When the preparation of the sample has not been done with sufficient care, several such treatments may be necessary to remove the last traces of scratches and bring out the sharpness desired. It has been found especially easy to produce good results by this etching method because of the excellent control offered by the slowness of its action and endless possibilities of re-touching and re-etching the sample without pitting it.

Etching Lead-Tin Alloys:

Although the warm dilute nitric-acetic acid solution was suitable for lead-tin alloys containing up to 3 per cent tin, an electrolytic etch using a 60 per cent solution of perchloric acid as electrolyte was found more satisfactory. This etch also brought out the structure of lead fairly well. The specimen is made a cathode with a coiled platinum wire as the anode. These electrodes are suspended about 2 in. apart in the electrolyte with a No. 6 dry cell as a source of energy. The time required for small specimens is from three-quarters to one and one-half minutes. Sufficient time must be allowed for removing the fine surface grains developed by the polishing operation but too much time will destroy the sharpness of the grain boundaries. The specimen should be finished by swabbing and drying as previously described.

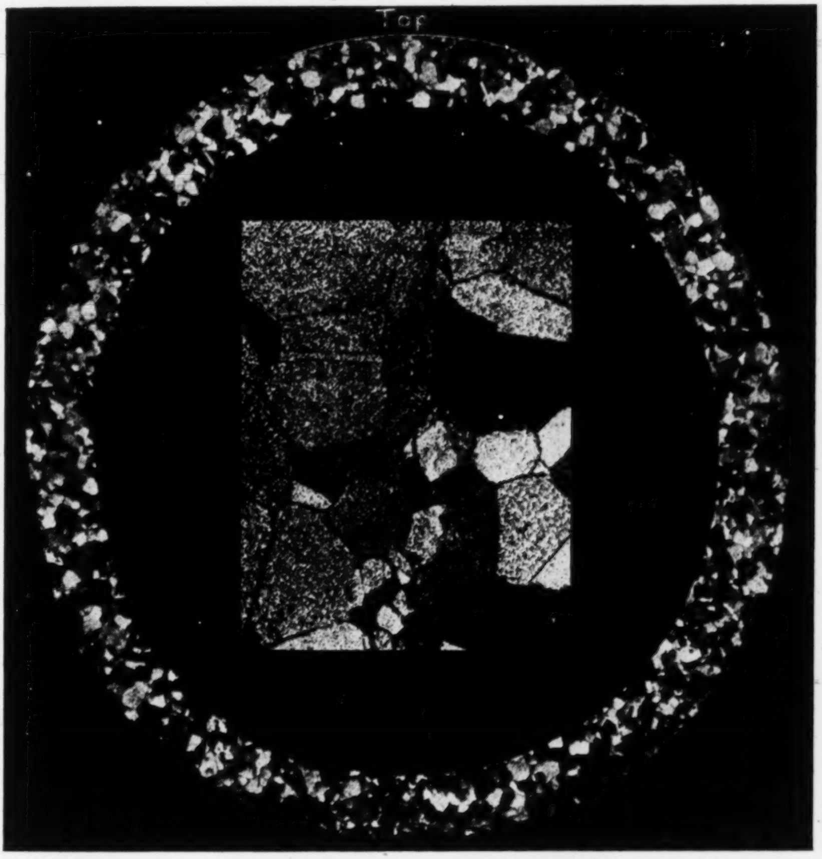

FIG. 1.—Cable Sheath 1 in. in Diameter (× 6½). Inset shows top weld (× 75). Both reduced 37 per cent in reproduction.

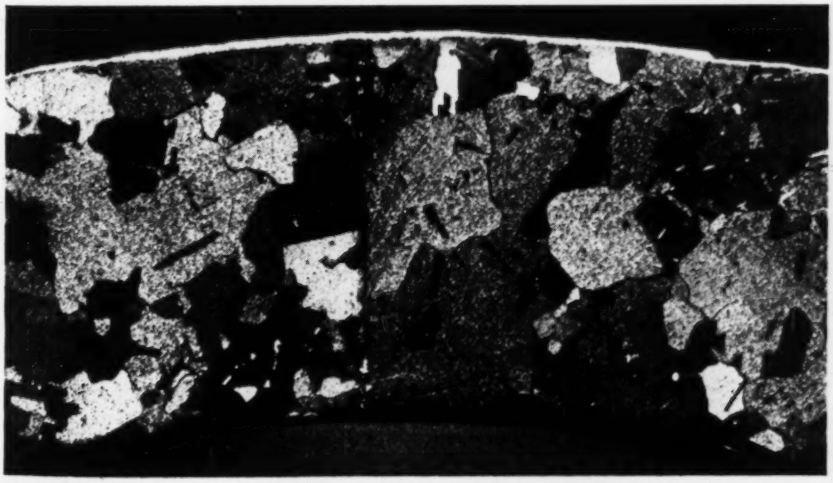

FIG. 2.—Top Weld in Lead Cable Sheath (× 20).

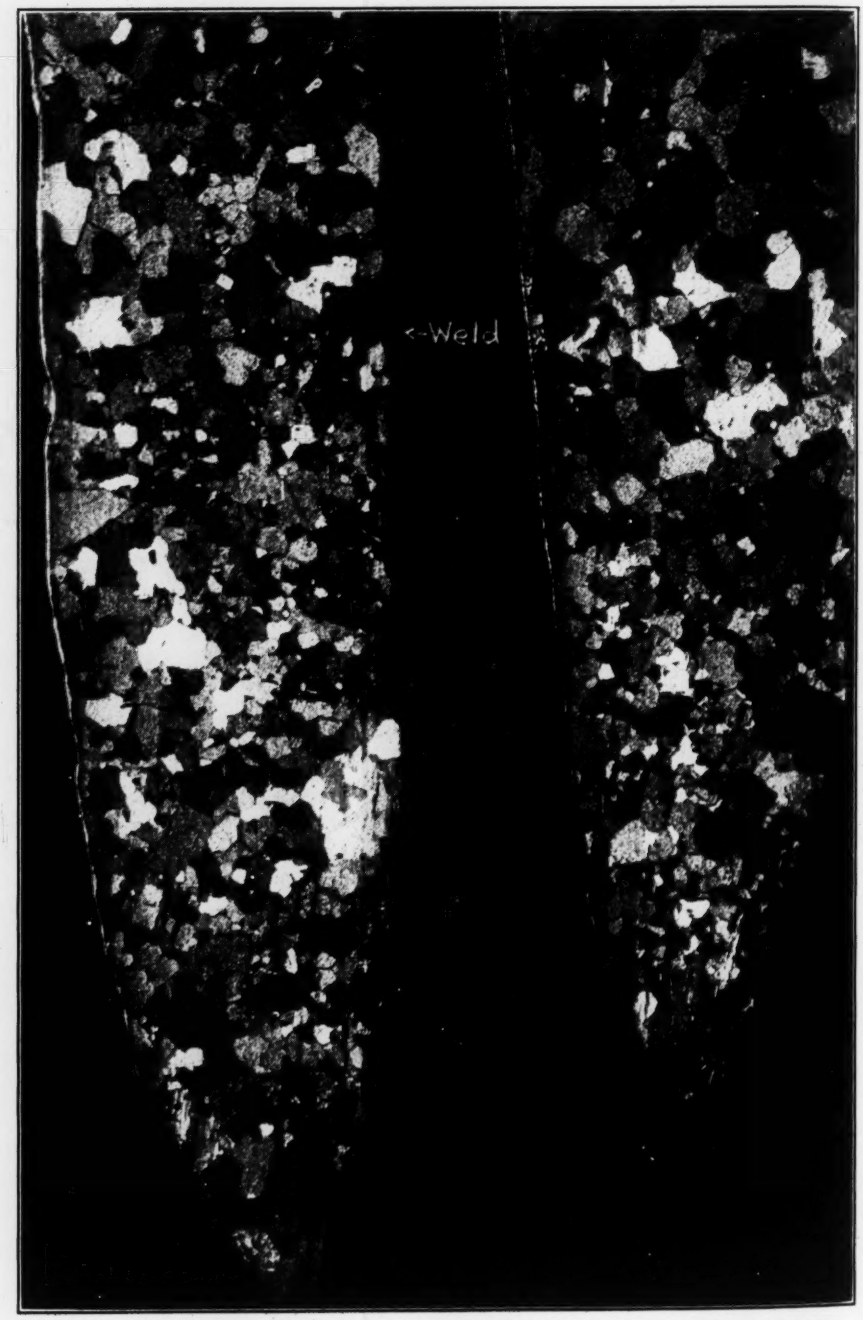

FIG. 3.—Tensile Break Demonstrating Strength of Weld Shown in Fig. 2 (× 20).

Etching Lead-Antimony Alloys:

The 50 per cent acid—9 per cent peroxide etch found best for lead-antimony alloys is prepared in two solutions. The surface to be etched is immersed in a solution *A* (Table I) for ten to fifteen seconds and then washed. The resulting black deposit is removed with a quick swab with solution *B* and the specimen immediately washed. Another dip of approximately one to two seconds in solution *A* and recleaning with solution *B* is advised, or in fact such alternate treatments may be continued with intermittent examination until the desired sharpness of structure is obtained.

EXAMINATION AND PHOTOGRAPHY

Examination of large areas of lead cable sheath for structural defects can be made satisfactorily at a magnification of 5 to 10 diameters using a 72-mm. focus lens. Considerable additional detail is revealed at 20 diameters using a 32-mm. focus lens. Close examination of grains and defects can be made with a 16-mm. focus lens at a magnification of 50 to 100 diameters, the latter being a relatively high magnification for lead and may show only one grain in a 4 by 5-in. field. Vertical illumination from a brilliant light source is recommended. Large areas are examined with light from a 15-ampere 110-volt arc projected by a 4-in. diameter lens system, the light being focused to just cover the area desired.

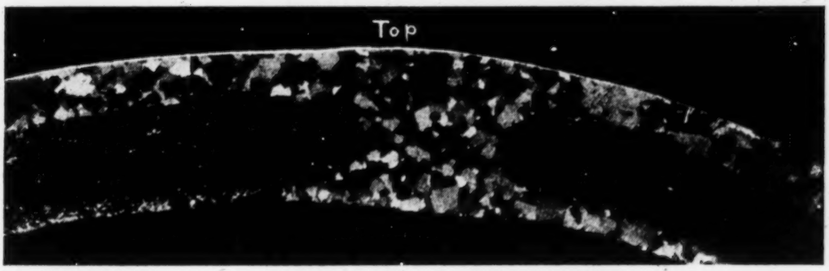

FIG. 4.—Top Portion of Lead Sheath Containing Long Oxide Streak (× 6½).

Photographs of structures at magnifications of 20 diameters or less can be made satisfactorily on ordinary slow plates without using a color filter. Pictures at greater magnification have a more pleasing appearance if a Wratten E (No. 22) filter is used and a panchromatic plate.

Examination of lead alloy cable sheaths, because of their finer grain structure, needs to be done at higher magnifications. Lead-tin

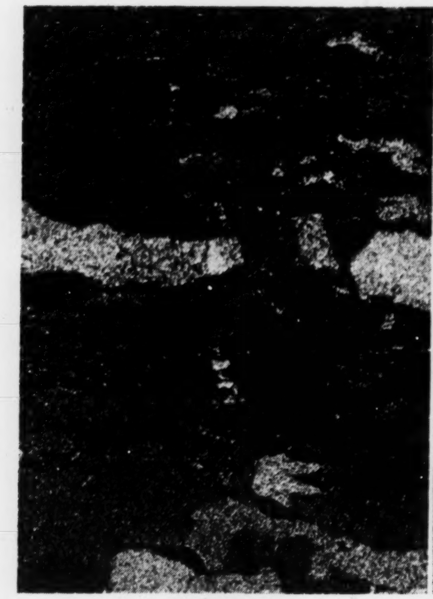

FIG. 5.—Detail of Oxide and Metal Shown in Fig. 4 (× 75).

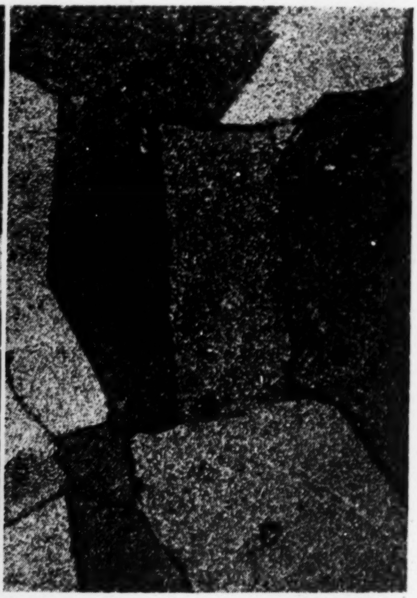

FIG. 6.—Normal Appearance of Lead Sheath (× 75).

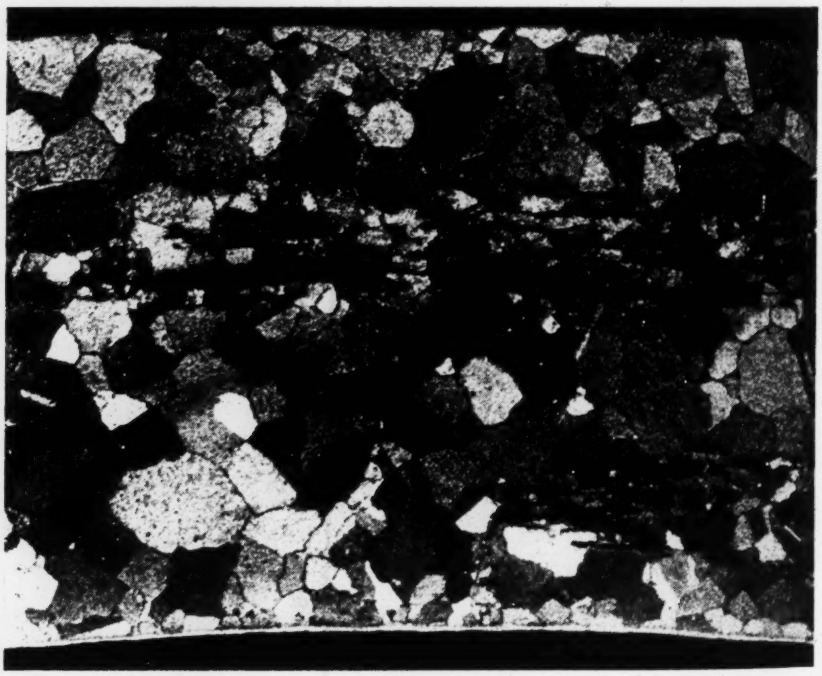

FIG. 7.—Laminations in Lead Sheath (× 20).

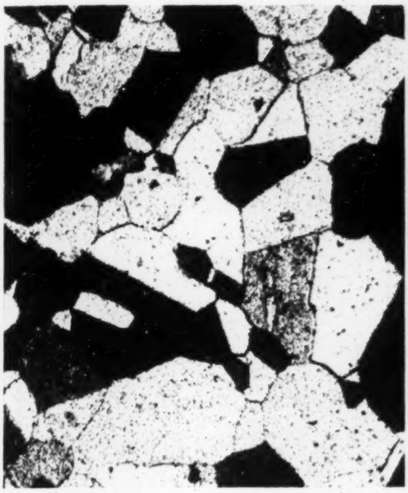

FIG. 8.—Normal Appearance of 2 per cent Lead-Tin Alloy Sheath (× 75).

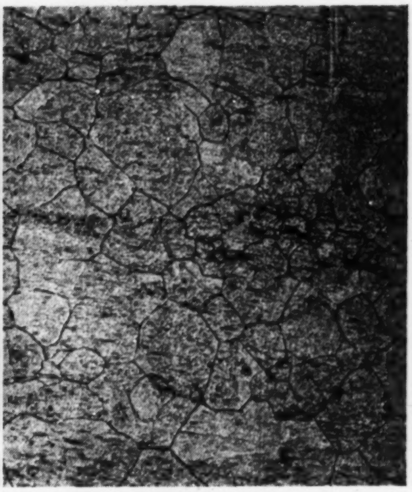

FIG. 9.—Normal Appearance of 1 per cent Lead-Antimony Alloy Sheath as Extruded (× 100).

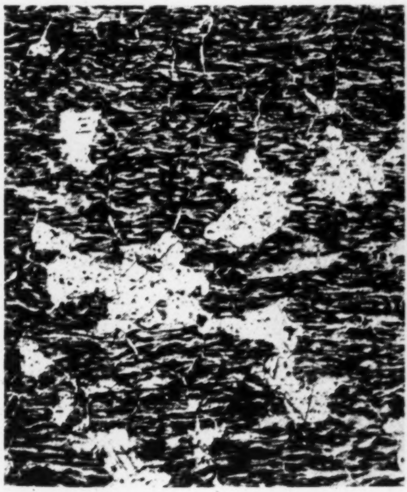

FIG. 10.—Severely Strained 1 per cent Antimony Alloy Sheath 18 Weeks Old (× 100).

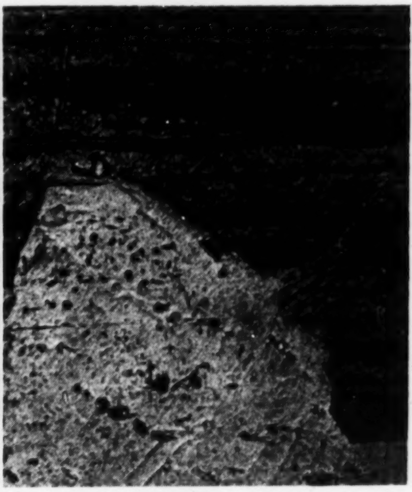

FIG. 11.—Enlargement at 500 Diameters of Duplex Structure in Fig. 10.

alloys can be studied at 20 to 200 diameters and lead-antimony alloys at 50 to 500 diameters.

The accompanying Figs. 1 to 11 illustrate the results obtained by the methods of examination described and also show the characteristic cross-sectional appearance of some irregularities occasionally found in lead cable sheath.

Acknowledgments.—The authors wish to thank Mr. E. L. Munson and others associated with The American Brass Co. for valuable suggestions.

REFERENCES

(1) F. F. Lucas, *Proceedings*, Inst. Metals Division, Am. Inst. Mining and Metallurgical Engrs., p. 481 (1927).

(2) J. R. Vilella and D. Beregekoff, "Polishing and Etching Lead, Tin, and Some of Their Alloys for Microscopic Examination," *Industrial and Engineering Chemistry*, Vol. 19, No. 9, p. 1049 (1927).

(3) J. M. Hodge and R. H. Heyer, "The Lead-Zinc Eutectic," *Metals and Alloys*, Vol. 2, No. 5 (1931).

(4) Rutherford, "Etching Lead and Lead Alloys," Bibliography of Etching, *Proceedings*, Am. Soc. Testing Mats., Vol. 24, Part I, p. 739 (1924).

(5) R. S. Dean, L. Zickrick and F. C. Nix, *Transactions*, Am. Inst. Mining and Metallurgical Engrs., Vol. 73, p. 505 (1926).

DISCUSSION

MESSRS. E. E. SCHUMACHER[1] AND G. M. BOUTON[1] (*presented in written form*).—Messrs. Bassett and Snyder are to be commended for collecting and collating the available data on methods of preparing lead and lead alloys for microscopic examination. We, at Bell Telephone Laboratories, are especially interested in this paper since the subject matter pertains to a field which we have been diligently investigating for a good many years in connection with cable sheathing studies. Since our methods of examining specimens are different in some respects from those given in this paper, it seems desirable to cite some of our experiences. To this end, we are relating what equipment is preferable, how lead specimens are prepared for microscopic investigation, what etching reagents are believed to be best, and how these reagents are applied. Photomicrographs are incorporated which show the results obtained. By thus submitting our information, it is hoped that interest will be stimulated in other workers to try the various methods described and to grade them. When this has been done, it may be possible to set up standard procedures.

The microtome method as described by F. F. Lucas in various papers is preferred and recommended for preparing lead surfaces for microscopic examination. All photomicrographs given in this discussion are of surfaces prepared with an inexpensive biological microtome which has been found to function satisfactorily for practically all purposes. If this instrument is not available, a wood chisel and special clamp may be used but somewhat less satisfactorily. In our experience in preparing thousands of specimens of various sizes and shapes there has been no case where these methods were found unsatisfactory. In years past, polishing methods have been used and found to be time consuming and inadequate, especially for studying dross inclusions and fatigue cracks in cable sheath.

If the microtome is used, certain precautions are necessary. The specimen should be clamped so that the knife cuts diagonally. The specimen after the final cut should be removed from in back of the knife to prevent working the freshly cut surface. The time required for preparing a section is not more than two or three minutes. With a limited personnel, hundreds of specimens can be examined monthly. To secure a satisfactory section, the microtome knife must be sharp. The sharpening may be done on a set of stones. If the stones are not available, as satisfactory results can be obtained with French emery paper suitably mounted. Rough grinding is done on No. 1 and the finishing on No. 00 paper. A few strokes on a leather strip completes the operation. The accompanying Fig. 1 is a photomicrograph of fatigue cracks in a lead, 0.5 per cent antimony, 0.25 per cent cadmium alloy and illustrates nicely how well the microtome prepares the surface to reveal these cracks.

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[1] Metallurgists, Bell Telephone Laboratories, Inc., New York City.

The chisel method, mentioned on page 559 of the paper, has given excellent results when properly used. The specimen is mounted in a hardened tool steel clamp. The specimen is clamped in place and the excess material removed with a coarse hacksaw. A rough chisel cut is made, followed by a fine one using the surface of the clamp as a guide.

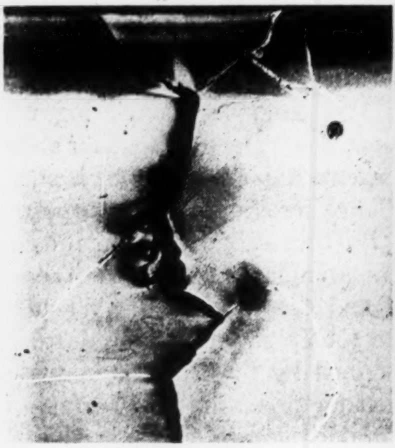

FIG. 1.—Photomicrographs of Intercrystalline Fatigue Cracks in a Lead, 0.5 per cent Antimony, 0.25 per cent Cadmium Alloy (X 125). The microtome is especially valuable for this type of work.

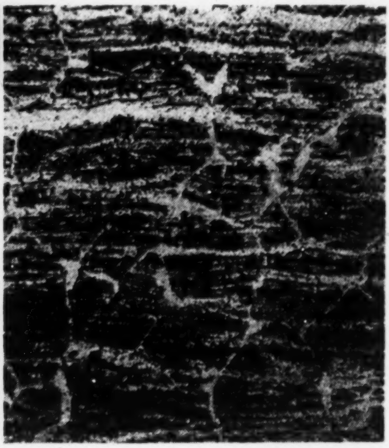

FIG. 2.—Photomicrograph of Aged Lead, 1 per cent Antimony Sheathing (X 125). The specimen was cut on a microtome and etched as described in the text.

The soap film has not imparied the detail.

Etching.—The methods of etching for lead-antimony and lead-calcium alloys used at Bell Laboratories have been mentioned on pages 560 and 561 of the paper. To obtain satisfactory results, however, certain details of the process must be observed. These details are different for the different commercial cable sheathing materials. In general, specimens prepared using both the microtome and the chisel show knife marks at low magnification. These may be eliminated to some extent by swabbing with cotton well soaked in a 3:1 glacial acetic acid - superoxol solution prior to the final etch. The etching modifications necessary with the various alloys are described below.

For etching pure lead a 3:1 glacial acetic acid - superoxol etch followed by a rinse in water is entirely satisfactory.

In etching lead-antimony alloys, the procedure depends to a great extent on the state of precipitation and agglomeration of the antimony. In general, the same etch is used as for pure lead. If a black deposit is obtained a larger proportion of superoxol should be used. If a white deposit is obtained, a larger proportion of acetic acid is required. The etch should be followed by a water rinse.

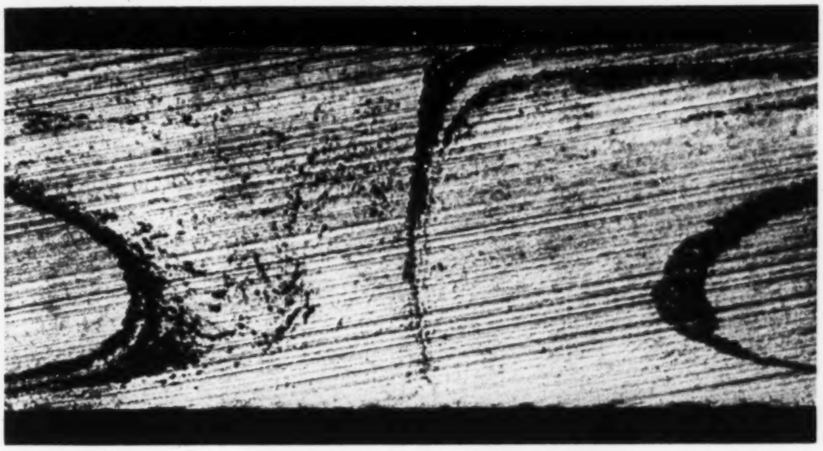

FIG. 3.—Macrograph of Dross Inclusions in Lead, 1 per cent Antimony Sheath (×16).

The lines left by the microtome are in evidence but it will be noted that the knife has not caused any distortion or dragging of the particles of dross as it passed through them.

A freshly etched lead-antimony surface has a great tendency to tarnish, especially in humid weather. This can be prevented by dipping the rinsed specimen in a dilute soap solution. A transparent film forms which prevents the attack of moisture and which does not change the appearance of the specimen under the microscope. The use of strong sodium hydroxide solution, mentioned on page 560 of the paper, we have found to be particularly useful for removing particles of antimony which adhere to the etched surface as well as general tarnish.

Two typical sections of lead-antimony cable sheathing alloy prepared in the manner described are shown in the accompanying Figs. 2 and 3. In preparing the section shown in Fig. 2, the etch and rinse was followed by application of the soap solution. The details are preserved during photographing and a well-defined structure typical of extruded lead-antimony results. Figure 3 shows a section of freshly extruded sheathing as revealed by this method of preparing the specimen.

For lead-calcium the same etch is used as for pure lead. After etching, however, the specimen is rinsed in ethyl alcohol for five seconds. This is followed by a rinse in water. The purpose of the intermediate alcohol rinse is to remove the etching reagent which, if not removed in the dilute water solution formed by the water rinse, would tarnish the freshly etched surface.

The etch reveals dross inclusions and also micro-constituents in the alloy. It does not, however, greatly attack the grain boundaries.

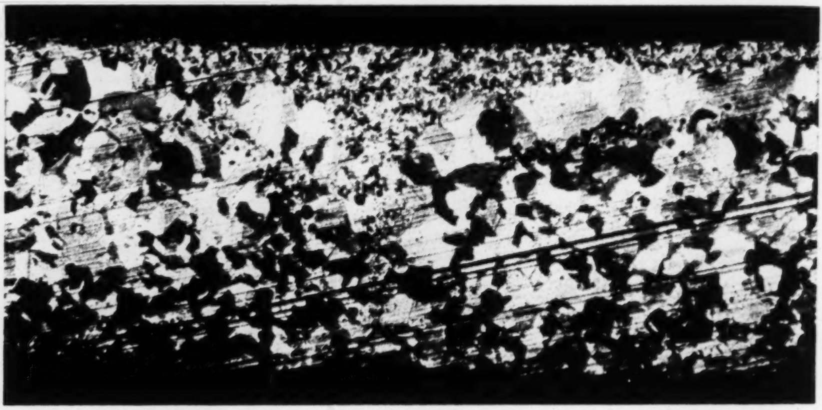

FIG. 4.—Macrograph of Grain Structure in Lead-Calcium Cable Sheath (× 16).

This shows clearly that the irregularities of the knife blade pass through the grains of the material without disturbing their structure. It is quite improbable that a polishing method would reveal the fine grain structure shown in the upper central portion of the picture. This picture is one of 75 that were taken one day by one man who also did all of the cutting and etching of specimens.

Grain structure is revealed satisfactorily by either of the methods described on page 561 of the paper. It has been our experience that slightly better results can be obtained with the second method using 1:1 nitric acid water solution subsequent to the etch to reveal dross inclusion. A section of lead-calcium sheath etched according to the described method is shown in Fig. 4. The dross inclusions are clearly defined; the grain structure which was developed by the nitric acid etch is clear and crisp. This is one of 75 pictures prepared in one day by one technician doing all operations including microtoming, etching and photographing. Besides the time saved by microtoming, another saving can be made by using film packs rather than plates for taking macrographs. Figures 3 and 4 show the detail that can be brought out in this type of film.

The structure of lead-tin is best revealed by the 3:1 glacial acetic acid - superoxol solution. Since there seems to be a considerable tendency for a surface recrystallization caused by working of the knife, a relatively long (10 to 20 seconds) etch is used. The specimen is rinsed in a 6:1 ethyl alcohol superoxol solution. This solution appears to give better results than an ethyl alcohol rinse alone. Figure 5 shows the typical structure of lead-tin revealed by this etch. The boundaries are sharp and the crystal detail crisp.

Drying.—The general practice of dipping the wet specimen in alcohol prior to drying in our experience has proved unsatisfactory for lead specimens in that some staining practically always occurs. Best results are obtained by drying the water-wet specimen directly in a blast of oil-free high pressure air.

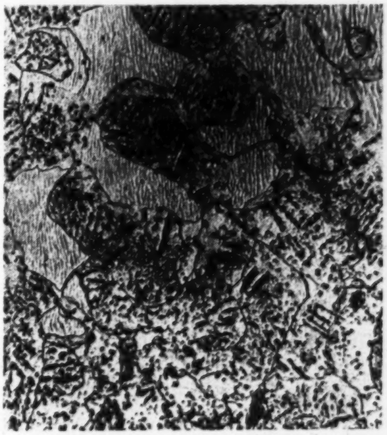

FIG. 5.—Photomicrograph of Lead, 3 per cent Tin Cable Sheath as Extruded (× 125).

The needle-like structure is typical of samples of all lead, 3 per cent tin alloys examined by us at the laboratories.

MR. W. A. COWAN.[1]—The micrographs shown by the authors are exceedingly well prepared and the preparation of lead alloys for microscopic examination may well be called an art rather than a mechanical process. The authors have shown that they have prepared excellent micrographs by their method and it is very proper that a description of the method should be published.

The illustrations for the article show the occurrence of some irregularities in cable sheath. It might be expected on this account that the paper would be followed by one showing the results of an investigation of the frequency of occurrence of defects in cable sheaths. The present paper simply describes the method of preparation of the specimens.

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[1] Assistant Chief Chemist, National Lead Co., Brooklyn, N. Y.

MR. W. H. BASSETT, JR.[1]—I want to thank Messrs. Schumacher and Bouton for their description of their methods of preparing samples. As stated, there is one great difference between the nature of their work and the work which we have done, namely, that most of the cable sheaths the Western Electric Co. uses are alloy sheaths whereas in the power cable field we devote most of the work to pure lead. Mr. Zickrick of the General Electric Co. has been using a microtome as was described and is obtaining very satisfactory results on the pure lead used for power cables.

The methods we described, however, have been satisfactory for all work so far undertaken. For example, in the past two years we have been able to improve the structure of lead cable sheath very considerably by controlling the casting practice when flowing the lead into the cylinder of the lead press. When we first started to study this matter we found at the junction of two charges of lead a considerable accumulation of lead oxide, and an area somewhat similar to Fig. 4 of the paper was quite common. We have found, however, that this wide flow line and oxide streak can be practically eliminated by watching mill operations.

In every case we prepare the full cross-section of a cable sheath, often examining rings taken from sheaths 3 in. in diameter, so that we can study in detail the entire structure and note any irregularities, some of which might be lost if only small sections from a sheath were studied. The number of samples that can be prepared, examined and photographed in one day by one operator will vary with the size of sheath and type of structure, but will average between six and twelve for sheaths taken from paper insulated power cables. If only visual microscopic examination is desired, many more examinations can be done in the same length of time. Mr. Legge of the American Steel and Wire Co. has used a similar method of studying complete rings, and has prepared some very interesting photographs showing flow lines and oxide inclusions, which were recently discussed at a committee meeting of the Insulated Power Cable Engineers Association.

In answer to Mr. Cowan's remarks we have found that the thickening of the flow lines and oxide streaks generally occurs in the first quarter of an extrusion charge; also some piping may occur in the last quarter of an extrusion charge. We hope in the future to present another paper showing these characteristics.

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[1] Technical Superintendent and Metallurgist, Anaconda Wire and Cable Co., Hastings-on-Hudson, N. Y.

(*Author's closure by letter*).—We agree with most of the points which are outlined in Messrs. Schumacher's and Bouton's discussion. It seems desirable, however, again to emphasize the fact that the number of samples that can be prepared by polishing, examined and photographed in one day by an operator is dependent on the size of the specimens, composition of the sheath and the quality of the work which he produces.

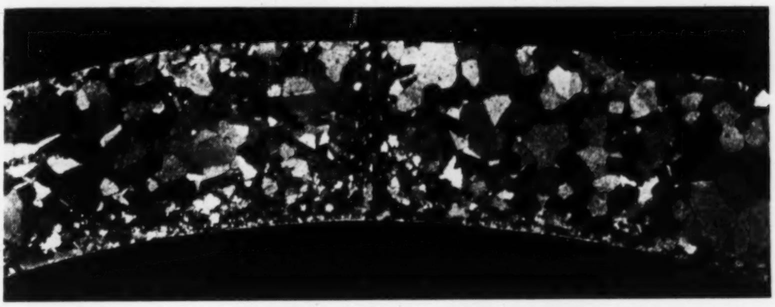

FIG. 6.—Macrograph of Grain Structure in Top Portion of Commercial Lead Cable Sheath (× $6\frac{1}{2}$).

The accompanying Fig. 6 shows the appearance of a commercial lead cable sheath which was prepared by the polishing methods described in the paper. It will be noted that this sample contains a fine grain area similar to the Macrograph of Grain Structure in Lead-Calcium Cable Sheath, shown in Schumacher and Bouton's Fig. 4. This shows clearly the uniform structure of normal cable lead sheathing and the fine grain area in the region of the weld.

EFFECT OF COLD WORKING ON THE IZOD NOTCHED-BAR IMPACT VALUE OF MONEL METAL

By N. B. Pilling[1]

Synopsis

The notched bar Izod value of monel metal is first increased and then decreased by cold working. The maximum occurs at about 10 per cent reduction by cold work, corresponding to a Brinell hardness in the range 155 to 175.

Stress relief annealing increases both the hardness and impact value.

Impact properties of drawn rods are sensibly uniform and do not depend upon the relative direction of bending.

Impact properties of rolled flats are highly directional and depend upon the position of the notch with respect to the axes of rolling. Impact value is greatest when the notch lies parallel to the breadth dimension of the flat.

The correlation between hardness and Izod value is good only when working is followed by a low-temperature anneal. Under these circumstances the Izod value is closely related to the apparent Brinell hardness of the fiber parallel to the bottom of the notch.

Among the important properties of the nickel-copper alloys of high nickel content, such as monel metal, are toughness and freedom from brittleness under many conditions of practical use. In association with other qualities including high strength at atmospheric and elevated temperatures, and resistance to many forms of corrosion, this group of alloys finds numerous applications in the engineering and process industries in which its dependability is enhanced by its capacity to absorb shocks and impact without fracture and with comparatively little deformation. Such applications as propeller shafts and blades, jordan knives, engine bolts, pump valves and turbine blading suggest the importance of this secondary property. Unlike most steels, this quality of great impact toughness persists in nickel copper alloys to low, sub-atmospheric temperatures, and unlike the softer copper alloys, it is substantially retained to temperatures above a red heat.[2]

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[1] Metallurgist, International Nickel Co., Bayonne Laboratory, Bayonne, N. J.

[2] Discussions of these and other impact properties of monel metal may be found in the following:

D. J. McAdam, Jr., "Endurance and Impact Tests of Metals," *Proceedings*, Am. Soc. Testing Mats., Vol. XVI, Part II, p. 292 (1916).

R. G. Waltenberg, "Notched Bar Tests and Toughness of Monel Metal," *Chemical and Metallurgical Engineering*, Vol. 25, p. 322 (1921).

R. G. Waltenberg, "Measuring Metal's Resistance to Shock," *Chemical and Metallurgical Engineering*, Vol. 31, p. 657 (1924).

R. H. Greaves and J. A. Jones, "The Effects of Temperature on the Behavior of Metals and Alloys to the Notched Bar Impact Test," *Journal*, Inst. Metals, Vol. 34, p. 85 (1925).

H. J. Tapsell and J. Bradley, "Mechanical Properties at High Temperatures of an Alloy of Nickel and Copper with Special Reference to Creep," *Journal*, Inst. Metals, Vol. 35, p. 75 (1926).

H. W. Russell and W. A. Welcker, Jr., "Endurance and Other Properties of Some Alloys for Aircraft Use," *Technical Note No. 381*, U. S. National Advisory Committee of Aeronautics (1931).

Impact tests have received much critical study, and the simple nature of the more usual forms of test contrasts with the lengthy discussions of their true significance which have occurred.[1] In this brief paper the usefulness of the impact test to the metallurgist and to the engineer will be taken for granted, and attention restricted to a demonstration of the extent to which the manner and degree of cold working affect the notched bar Izod value of monel metal.

MATERIAL FOR TEST

Two pieces of hot-rolled monel metal, a rod and a bar, were selected, which showed by analysis:

	NICKEL, PER CENT	COPPER, PER CENT	IRON, PER CENT	MANGANESE, PER CENT	SILICON, PER CENT	CARBON, PER CENT	SULFUR, PER CENT
Rod..............	67.54	29.41	1.55	1.35	0.02	0.10	0.005
Bar..............	67.80	29.29	1.59	1.19	0.01	0.09	0.010

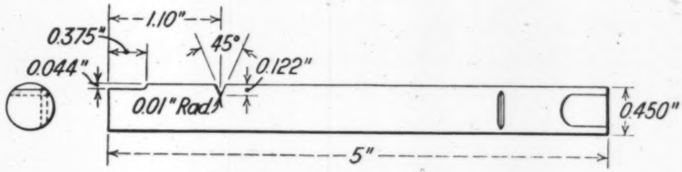

FIG. 1.—Test Specimen.

Both pieces (12 ft. long) were annealed 45 minutes at 1500° F. The 1-in. rod was then cold drawn in 4 drafts to 0.75 in. in diameter, an 18-in. length being cut off after each draft. The bar, originally 1 in. thick by 2 in. wide, was rolled in a cold strip mill by 5-per-cent reductions to 30 per cent reduction, and then by 10-per-cent reductions to 50 per cent. Each reduction was accomplished in a single pass through the rolls, and an 18 in. length was cut after each pass.

About half of each sample was subjected to a "strain-relief" anneal, consisting of holding 2 hours in oil at 575° F. Later references to "heat-treated" specimens refer specifically to this one treatment.

TEST SPECIMEN

Standard round V-notch Izod test specimens were prepared (Fig. 1), one from the metal as cold worked, another after the strain relief heat treatment. They were cut from the center of the cross-section, the long dimension of the test specimen being parallel to the direction of rolling or drawing. Each specimen had two notches placed at right angles to each other. In the case of the rolled flats one of these was parallel to the thickness dimension. This arrangement is shown in the sketches of Fig. 2.

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[1] Symposium on Impact Testing of Materials, *Proceedings*, Am. Soc. Testing Mats., Vol. 22, Part II, p. 5 (1922).

Brinell and Rockwell hardnesses were measured on separate portions cut for the purpose. On flats, measurements were made on a cross-section; on rods, upon a cross-section and an axial longitudinal section; and a number of hardness measurements taken on the external longitudinal surfaces of both are recorded. In certain of the more severely cold-rolled portions the Brinell impression came out oval (long axis parallel to width of flat) and since no more refined treatment was needed, the directional differences in hardness indicated are recorded merely as the hardness numerals corresponding to spherical impressions having diameters equal to these longer and shorter axes.

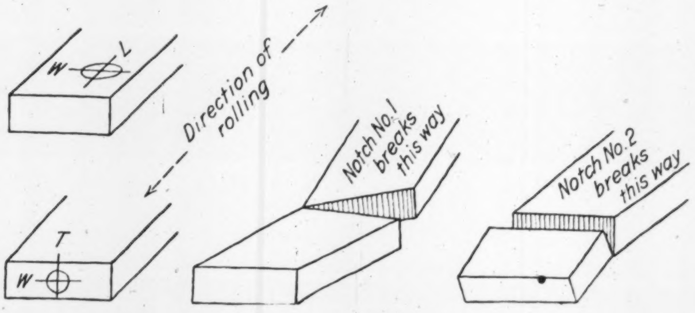

FIG. 2.—Brinell and Notch Orientations.

The specimens were all broken in the conventional form of Izod instrument.

EXPERIMENTAL DATA AND DISCUSSION

Details of the experimental data are given in Table I. It may be noted that the reduction by cold work was estimated as reduction in area in the case of rod, and reduction in thickness with the rolled flats. In the latter case a lateral spreading occurs which with the most severe reduction amounted to 6.5 per cent; it may roughly be considered that the elongation due to rolling occurs in two directions, longitudinal and lateral, the former greatly predominating. With this view of the matter, reduction in thickness should be, as a measure of cold work, quite comparable to area reduction by drawing, and the curves later shown bear this out.

TABLE I.—HARDNESS AND IZOD MEASUREMENTS.

Form	Condition	Diameter or Thickness, in.	Reduction by Cold Work, per cent	Hardness on Cross-Section					Brinell Hardness Number on Longitudinal Section	Hardness of Surface					Izod, ft-lb.[a]			
				Brinell[a]			Rockwell			Brinell[a]			Rockwell					
				In Direction of		Average	"B" Scale	"C" Scale		In Direction of		Average	"B" Scale	"C" Scale	Notch No. 1	Notch No. 2	Average	Fracture[c]
				Thickness	Width					Length	Width							
Rod	As drawn	0.975	0	...	...	112	69	−17	121	...	...	...	61[b]	−22[b]	86	92	89	no cracking
		0.938	7.3	...	...	154	83	+ 5	155	...	...	...	83	+6	113	112	113	slight crack
		0.875	19.4	...	...	179	93	12	187	...	...	...	87	10	102	101	102	partial fracture
		0.812	30.5	...	...	199	96	19	209	...	...	...	89	12	78	81	80	partial fracture
		0.750	40.7	...	...	207	98	23	217	...	...	...	90	14	72	76	74	partial fracture
	Heat treated 575° F., 2 hours	0.975	0	...	...	115	68	−17	117	...	...	...	57	−23	97	96	97	no cracking
		0.938	7.3	...	...	156	86	+ 9	158	...	...	...	85	+ 9	119	119	119	slight crack
		0.875	19.4	...	...	191	94	17	194	...	...	...	89	13	109	109	109	partial fracture
		0.812	30.5	...	...	211	99	22	217	...	...	...	92	16	81	76	79	partial fracture
		0.750	40.7	...	...	217	101	24	228	...	...	...	95	20	76	76	76	partial fracture
Flat	As rolled	0.990	0	120	120	120	68	−14	...	118	118	118	65	−13	88	90	89	no cracking
		0.950	4.0	143	143	143	77	− 1	...	145	145	145	80	+2	105	106	106	no cracking
		0.895	9.6	161	161	161	82	+ 6	...	164	164	164	84	7	113	112	113	slight cracking
		0.845	14.6	175	175	175	88	11	...	170	170	170	88	12	110	110	110	partial fracture
		0.800	19.2	186	182	184	89	13	...	179	179	179	89	13	97	98	98	partial fracture
		0.750	24.2	193	183	188	91	14	...	185	185	185	91	14	90	95	93	partial fracture
		0.700	29.2	204	187	196	91	15	...	184	189	187	91	13	78	85	82	partial fracture
		0.600	39.3	212	197	205	92	18	...	196	202	199	94	18	70	83	77	partial fracture
		0.500	49.4	219	196	208	93	19	...	196	207	202	95	18	58	74	66	partial fracture
	Heat treated 575° F., 2 hours	0.990	0	121	121	121	67	−15	...	117	117	117	66	−13	92	91	91	no cracking
		0.950	4.0	145	145	145	78	− 1	...	149	149	149	79	+ 2	115	113	114	slight cracking
		0.895	9.6	164	164	164	83	+ 7	...	167	167	167	84	6	119	115	117	partial fracture
		0.845	14.6	179	179	179	88	11	...	177	177	177	88	11	118	119	119	partial fracture
		0.800	19.2	191	187	189	89	12	...	182	187	185	89	12	105	113	109	partial fracture
		0.750	24.2	194	187	191	94	16	...	194	196	195	93	16	91	106	99	partial fracture
		0.700	29.2	207	199	204	92	16	...	194	196	195	92	15	82	90	86	partial fracture
		0.600	39.3	215	207	211	95	19	...	207	209	208	96	20	90?	82	82?	partial fracture
		0.500	49.4	224	211	218	97	20	...	215	224	220	97	22	66	78	72	partial fracture

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[a] See Fig. 1 for relation between position of Izod notch, Brinell diameter and axes of rolling.

[b] $\frac{1}{16}$ in. of surface had been removed.

[c] In no case was the break complete.

Effect of Cold Working:

The effect of cold working in its general features is shown by Fig. 3 (*a*). The outstanding characteristic is that impact strength is first increased and then decreased by working. The detail of this sequence, however, is rather complicated. The Izod strength of annealed monel metal is about 90 ft-lb., a value, incidentally, considerably below that of the hot-rolled alloy. Considering for the moment working by cold rolling, the Izod value rises rapidly to a maximum at about 10 per cent reduction and then decreases rather less rapidly. At 25 per cent reduction, the impact strength is numerically the same as the original (annealed) value; however, the former

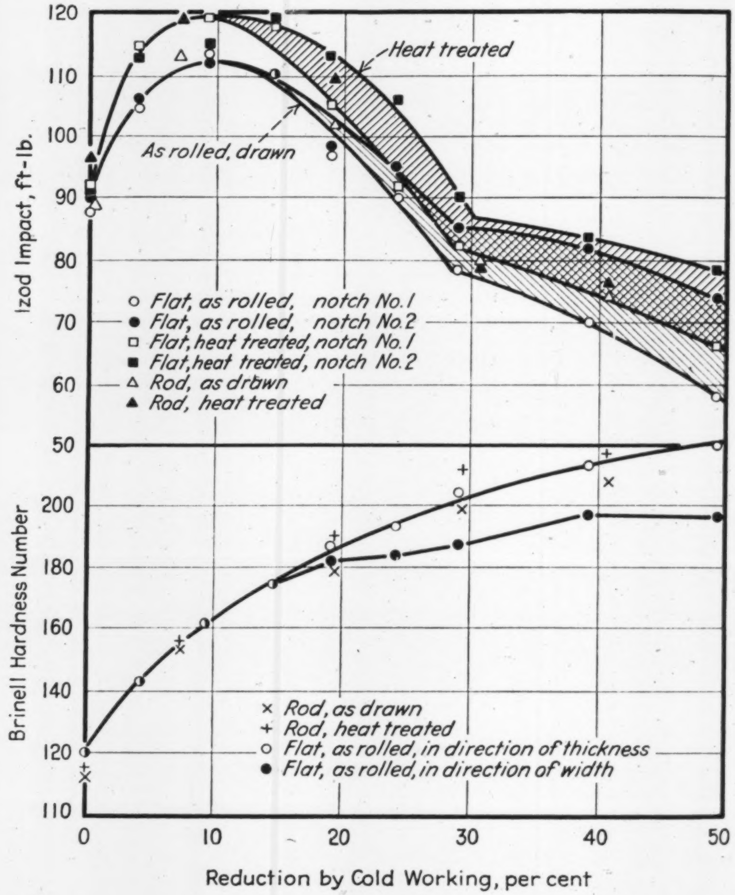

FIG. 3.—Effect of Cold Working on Izod Impact and Brinell Hardness.

cracks at the blow, while the latter does not. At 30 per cent reduction, a sharp change in the magnitude of the cold working effect occurs and greater reductions have a rather mild effect in further reducing the Izod reading. It will be noticed that the direction the specimen is bent with respect to the breadth and thickness of the rolled strip has no effect until the maximum on the curve is passed and that beyond this a clear division occurs, the impact strength being consistently greater when the bend is made across the thickness of the strip with the axis of bending parallel to the width dimension. The amount of this fiber effect, or difference in strength in different directions, becomes greater as the amount of working increases, and at 50 per cent reduction in thickness the rolled strip may be over 20 per cent weaker along the thickness axis. The impact strength of the more highly cold-worked metal is thus somewhat indeterminate when the notch is in a random position, lying in the shaded area between the two limiting curves.

Tests on the cold-drawn rod are quantitatively similar to the rolled material, but without fiber effects, the two notches generally agreeing closely. It is of interest to see that the cold-drawn rods follow the break in the curve at 30 per cent reduction; this is evidence that the effect is a real one and in all probability is not related to the circumstance that the rolled strip received heavier reductions per pass in rolling beyond 30 per cent. The change in hardness with cold rolling is shown in Fig. 3 (*b*). No clear indication of change in rate of hardening at 30 per cent reduction is evident, but it is perhaps important to find that the more heavily worked strip gave oval Brinell impressions on the cross-section. When the Brinell number was computed from the diameter parallel to the thickness dimensions (also parallel to Izod notch No. 1), the hardness-reduction curve was continuous and in fairly close agreement with the hardness of the rods worked by cold drawing. Hardness in the direction of width departed widely from this curve.

The shape of the Izod-reduction curve, Fig. 3 (*a*), bears a simple and obvious relation to the appearance of the fracture. The Izod test measures work done and therefore involves a force and a distance component. As annealed monel metal bends but does not break in the Izod test, the hardening effect of cold work increases the force factor without diminishing the distance through which it acts and the impact strength rises. The maximum on the curve (10 per cent reduction) marks the point at which cracking first appears, and the subsequent fall in impact strength reflects the circumstance that the increasing hardness is more than offset by the increasingly smaller distance the specimen bends before it cracks.

Effect of Low-Temperature Annealing:

The heat treatment at 575° F. in general increases impact strength, Fig. 3 (*a*), but aside from shifting the curves to higher Izod values, does not change the rather complex relation between impact strength and percentage reduction. The disparity between notches placed parallel or transverse to the thickness persists undiminished. The effect of this heat treatment in increasing impact strength is most marked below 30 per cent reduction; above this, the improvement is very slight.

Relation Between Izod Value and Hardness:

It has already been remarked that the rolled material gave oval Brinell impressions, indicating that the hardness depended upon the direction in which it was measured. The strain relief anneal was found to result in an increase in hardness. It seemed desirable to trace the relation between hardness and impact strength, taking into account these various factors. In Fig. 4, the hardness of the rolled strip is plotted against the corresponding impact strength, the hardness measurement being taken to correspond to the direction of the notch (that is, Brinell diameter on cross-section parallel to notch direction). When thus plotted, these facts emerge:

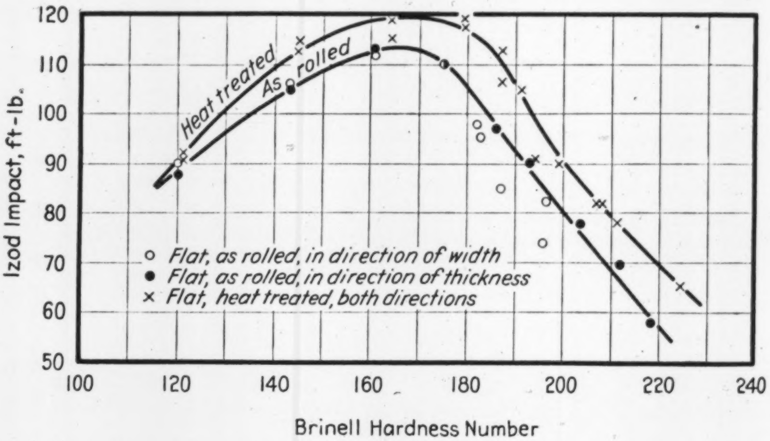

FIG. 4.—Relation of Directional Izod Impact to Directional Hardness. Bottom of Izod notch parallel to measured diameter of Brinell impression.

1. In the heat-treated specimens all directional properties vanish and the impact strength is closely related to the hardness of the fiber which parallels the notch bottom. While not plotted (to avoid confusion), the points for the heat-treated rods lie squarely on this curve also.

2. In the as-rolled condition, disparity persists between "thickness" and "width" data. The "thickness" data are found to correspond with the data from the cold-drawn rod.

3. Izod strength is not closely predictable from Brinell measurement unless a "stress-relief" anneal has been given. Lacking knowledge of heat treatment, method of working, amount of working and relative position of the notch, the impact strength of monel metal cannot be estimated from the hardness with a precision greater than 25 per cent, when the Brinell hardness is greater than 180.

While impact value is thus found to be sensitive to a number of factors regarding which information cannot always be had, the approximate relation between Izod impact value and hardness is of practical value. The Rockwell test is particularly unsatisfactory as a criterion as it is insensitive at the range of hardness where impact strength is most sensitive to hardness. The analysis of properties described above was made, for particular reasons, using the Brinell hardness of interior sections definitely related to the position of the notch, and these do not necessarily correspond closely to the hardness of the exposed, rolled surface. This, however, is perhaps the simplest measurement which can be made in a non-destructive, engineering inspection, and Fig. 5 represents the correlation found between the average impact value and the average surface Brinell hardness for this heat of monel metal. It is not intended to represent, however, either the average or minimum values for this type of material.

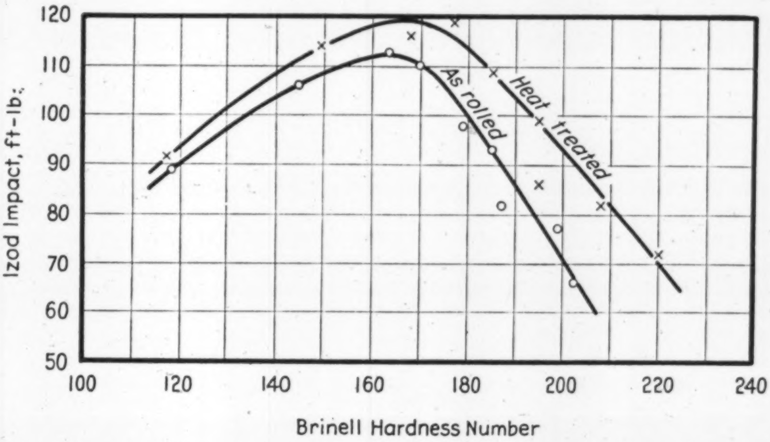

FIG. 5.—Relation of Average Izod Impact to Average Surface Hardness.

THERMAL EFFECTS IN ELASTIC AND PLASTIC DEFORMATION

By M. F. Sayre[1]

Synopsis

It has long been known that in materials loaded below the elastic limit, application of compressive stress causes a rise; and of tensile stress, a decrease, in temperature, but it has not been generally realized that these temperature changes also involved an elastic after-effect which took the form of a gradual creep in length as these temperature differentials become equalized. The so-called elastic after-effect and also elastic hysteresis is therefore in part at least due to a purely thermal cause, independent entirely of any defects in elastic behavior in the material itself. From the viewpoint of creep or hysteresis, it is suggested that the thermal creep be estimated and deducted from experimental results before attempting to draw any conclusions as to the laws which govern the non-thermal component of the creep or hysteresis. Estimates of the magnitude of the thermal creep are given. From the viewpoint of accurate stress-strain measurements, as in the use of elastic devices for calibration of testing machines, it is suggested that definite time schedules of work be adhered to in order to minimize the effect on accuracy of these two types of creep.

Above the elastic limit, stress variations continue to cause this first type of temperature change, but there is superimposed an increase in temperature resulting from the absorption of energy in plastic deformation within the material. For small percentages of elongation, this temperature rise due to plastic flow is not large; in fact, under most conditions, it is less than the temperature rise or fall which would accompany an equal unit elastic elongation. It differs, however, markedly in character, in that the elastic changes occur uniformly throughout the entire mass of the body, while the energy released in plastic flow is momentarily at least concentrated in the immediate neighborhood of the slip planes concerned. Along these slip planes, temperatures therefore rise for a brief fraction of a second to figures probably several thousand times higher than the average increase in temperatures which ultimately occurs in the entire mass of material. These temperatures in fact may and probably do rise high enough to have an important influence on the behavior of the metal. The exact values will be determined in a large measure by the speed with which the deformation is carried on and by the surrounding temperature conditions. It is suggested that unsatisfactory results in the past in studies of plastic flow may in part at least have been caused by incomplete control of these speed and temperature factors in testing.

An investigation into the elastic behavior of metals with special reference to spring materials has been under way at Union College for several years past in cooperation with and with backing from the Research Committee on Mechanical Springs of the American Society of Mechanical Engineers. Some of the results of that investigation were reported to the American Society for Testing Materials in June, 1930.[1]

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This work has naturally led to a study of the influence of various temperature effects on elastic and plastic behavior in metals. These temperature effects have been well known to physicists for some years past, but certain implications in connection with methods of testing which result from them have been surprisingly neglected.

So far as concerns materials testing, temperature plays four basically different rôles:

1. Actively, temperature changes cause expansion or contraction of the material, and so cause changes in length or volume;
2. Temperature changes cause changes in the different moduli of elasticity and affect the rate of change of length or volume under loading;
3. Passively, temperature changes occur as a result of any adiabatic, elastic, changes in volume, whether in gas, liquid or solid, and so accompany any cases of rapid loading or relief from load; and
4. Temperature changes result from any transformation of energy into heat, such as accompany all cases of plastic yield within the materials, whether small or large in amount.

The first two rôles are well understood, and call for no particular attention. The existence of the third is not as generally recognized, or where recognized is underestimated in amount. In particular, its secondary effect upon apparent mechanical hysteresis and elastic after-effect in materials, and also upon the precautions necessary to obtain accurate results in stress-strain measurements, as for example in the use of elastic devices for calibrating testing machines, call for attention.

In tension, compression, or bending, an application of load results in changes in volume. These changes in volume, if accomplished rapidly enough to be adiabatic in character, are accompanied by changes in temperature. The law governing these changes was first pointed out theoretically by Lord Kelvin(**1**).[2] According to this law any material which tends to elongate on heating, and this includes nearly all common materials, will drop in temperature on being subjected to a forced adiabatic elastic elongation, as by rapid application of a tensile load within the elastic limit. Similarly, a compressive load rapidly applied will cause a corresponding rise in temperature. A few materials, such as rubber under certain conditions, or invar, which when under load decrease in length with increase of temperature, will show the reverse effect, increasing slightly in temperature on rapid application of tensile loading within the elastic limit. The magnitude of this temperature change is given by the following equation:

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[1] M. F. Sayre, "Elastic Behavior of Spring Materials," *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part II, p. 546 (1930).

[2] The boldface numbers in parentheses refer to the reports and papers given in the list of references appended to this paper, see p. 592.

$$dT = \frac{T\,\Delta p}{Js\rho}\left(a + \frac{m(p_1 + p_2)}{2E}\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where dT = change in temperature,
T = absolute temperature,
E = Young's modulus of elasticity,
a = coefficiency of linear expansion with temperature,
m = temperature coefficient of modulus of elasticity,
s = specific heat,
ρ = density,
J = mechanical equivalent of heat,
p_1 = magnitude of initial unit stress,
p_2 = magnitude of final unit stress, and
Δp = change in unit stress = $p_2 - p_1$.

For the special case where the initial stress $p_1 = 0$, this equation becomes:

$$dT = \frac{Tp}{Js\rho}\left(a + \frac{mp}{2E}\right) = K_1 p\left(1 + \frac{mp}{2\alpha\,E}\right)$$

This corresponds to the equation given by Voigt (3,4). As already stated, this change in temperature may be either positive or negative, depending upon values of a and m and upon whether the stress applied is in compression or tension. It must be clearly differentiated from the change in temperature resulting from the absorption in energy in plastic flow, which is always positive in character. In case both elastic and plastic action are present, as above the elastic limit, the resulting change in temperature is the algebraic sum of the two factors.

Disregarding plastic flow components, the true unit change in length resulting from the rapid application of a tensile load will be the algebraic sum of the following factors:

1. The usual elastic elongation $\Delta p/E$, where E is the modulus of elasticity as determined under isothermal conditions, with loading very slowly applied, so that temperature can be treated as constant;
2. A decrease in length, $a dT$, resulting from the change in temperature given by Eq. 1;
3. A decrease in elongation, resulting from the change in modulus of elasticity with temperature, $mp_2 dT/E$;

4. An increase in elongation, resulting from the decrease in cross-sectional area caused by the decrease, dT, in temperature. This is small and may well be tacitly combined with item 3.

In the case of a compressive load, the factors involved are:

1. The usual elastic shortening $\Delta p/E$;

2. An increase in length, αdT, resulting from the change in temperature given by Eq. 1;

3. An increase in the deformation, resulting from the decrease in modulus of elasticity with increasing temperature, $mp_2 dT/E$;

4. A decrease in deformation, resulting from the increase in cross-sectional area with increase in temperature, which may as before be combined with item 3.

Combining these terms, substituting the value for dT as already given, and eliminating one minor term the net unit change in length under adiabatic conditions is found to be:

$$\frac{\Delta p}{E}\left(1 - \frac{\alpha^2 ET}{\rho sJ} \pm \frac{\alpha mT(p_1 + 3p_2)}{2\rho sJ}\right) \qquad (2)$$

$$= \frac{\Delta p}{E}\left(1 - K_2 \pm \frac{mK_1(p_1 + 3p_2)}{2}\right) \qquad (2a)$$

Here K_1 and K_2 are constants whose values for different materials are given in Table I. The negative sign before the last term should be used for increasing tension and the positive sign for the opposite change in stress. This last term, except for very large stress changes, is ordinarily very small in comparison to the preceding item, K_2, so that the percentage difference between the adiabatic and the isothermal change in length either in tension or compression can be considered as essentially expressed by the term K_2. Values of this term for different materials are given in Table I.

Changes in length on the tension and compression sides of the neutral axis in bending are given also by Eq. 2, the negative sign before the last term being used as before for tension and the positive sign for bending. A relatively simple deduction indicates that the percentage difference between the adiabatic and isothermal deflections in the beam will also be expressed by the same term K_2.

In other words, in all but a few special cases, as invar and some forms of rubber, the adiabatic modulus of elasticity is greater than the isothermal modulus in the ratio 1 to $1 - K_2$, and the instantaneous elastic elongation under rapidly applied loads is less than the isothermal elongation in the reverse ratio. This difference in elongation, however, is the result of the temperature differentials between different parts of the specimen or between the specimen and the surrounding atmosphere. As these temperature differentials later gradually disappear through a normal equalization of temperature by conduction or convection, there will be a gradual creep of the specimen, so that ultimately the isothermal value of elongation will be attained. The rate at which this creep occurs will depend upon the thermal conductivity of the material, and for any given case can be readily computed.

For comparison with the computed values of thermal creep given in Table I, a number of typical values for the total elastic after-effect in tension, including both the thermal and the pseudo-elastic components, obtained at Union College in connection with the investigation already mentioned, are given in Table II. These values were obtained working under controlled temperature conditions with dead-weight loading and a gage length of 15.7 meters. Under these conditions, the sensitivity has been one part in 30,000,000 and the probable precision one part in 1,500,000 on the total length. With this sensitivity, the elastic after-effect, even at loads far below the elastic limit, becomes strikingly apparent.

TABLE I.—APPROXIMATE VALUE OF COEFFICIENTS FOR VARIOUS MATERIALS.

Material	Density, ρ	Specific Heat, s	Coefficient of Linear Expansion, $a \times 10^{-6}$	Modulus of Elasticity, E, lb. per sq. in. $\times 10^{-6}$	Thermal Coefficient of Modulus of Elasticity, m, $\times 10^{-4}$	K_1, $\times 10^{-6}$	K_2, $\times 10^{-3}$
Magnesium	1.74	0.24	25.8	6.25	9.4	29.80	4.80
Aluminum	2.70	0.21	23.1	10	5.3	19.64	4.54
Iron	7.88	0.102	11.7	30	3.27	7.02	2.46
Nickel	8.9	0.102	13.2	30	2.6	7.02	2.78
Copper	8.93	0.091	16.8	17.8	3.59	10.00	2.99
Tungsten	19.3	0.034	4.44	55	0.87	3.27	0.80
Platinum	21.37	0.030	8.99	23.5	0.73	6.77	1.43

NOTE 1.—Values of a and m are given per 1° C.

NOTE 2.—$J = 4.185 \times 10^7$, $K_1 = \frac{CaT}{\rho s J}$, C, conversion factor from dynes per square centimeter to pounds per square inch $= 6.894 \times 10^4$, $K_2 = \frac{Ca^2ET}{\rho s J}$.

NOTE 3.—Ambient temperature, T, taken as 20° C. or 293 deg. Abs.

TABLE II.—VALUES OBTAINED AT UNION COLLEGE.

	Diameter, in.	Load Added, lb.	Elongation, mm.	After-Effect, mm.	Ratio, After-Effect to Elongation, $\times 10^{-3}$
Spring steel, 0.67 per cent carbon, heat treated	0.028	10	8.6	0.006 to 0.012	0.7 to 1.4
Premier spring steel	0.042	40	15.3	0.077 (loading)	5.0
				0.039 (unloading)	2.6
Hard copper wire	0.051	4	1.66	0.026	15.6
		10	4.14	0.038	9.2
		20	8.28	0.071	8.6
Aluminum wire (17SRT)	0.065	10	4.7	0.0144	3.06
		40	18.8	0.0713	3.79

Except in the one case noted in the table, these measurements represent the amount of delayed elastic recovery which occurred on suddenly reducing the load by the amount noted. An initial reading was taken as rapidly as possible after removing the load, usually within 6 seconds, and others thereafter over a period of 5, and in some cases 10 minutes. Each figure given represents an average of a number of such readings. Values on unloading rather than on loading are given in order to reduce to a minimum the effect of the gradual non-elastic creep which to a minor degree was in many of the cases occurring simultaneously.

In all observations of creep or elastic after-effect, therefore, made by the usual method of rapidly applying a load and thereafter measuring the time rate of change of deformation, part at least of the observed creep will be due to this purely thermal cause and will have no connection with any deviations from perfect elasticity in the material. Noting the values of K_2 given in Table I, the relative magnitude of this thermal creep is seen to range from 0.080 to 0.48 per cent of the elastic elongation, being about 0.2 per cent for steel. The rate of this creep will depend upon the rate of thermal equalization, being greatest at the start when the temperature differentials are high, thereafter decreasing according to a logarithmic law with respect to time.

Creep of this nature also involves the existence of mechanical hysteresis. Both creep and mechanical hysteresis are therefore explainable in part by this thermal mechanism, and to that extent therefore cannot be avoided by any improvements made in the elastic characteristics of the material used. As indicated in the last column in Tables I and II, this thermal component is large enough in comparison with the total short-time creep as to be usually not negligible, and in some cases it conceivably might explain the total amount. It will not however completely explain such cases as mechanical hysteresis in shafting revolving at high speeds where temperature equalization has no time to occur, nor long-time creep extending over periods of days, long after the initial temperature differentials have disappeared. The evidence therefore is strong that ordinarily both this thermal creep and a pseudo-elastic or plastic creep occur simultaneously.

To the students of creep or mechanical hysteresis, the significance of these facts are two-fold: first that when stressing in tension, compression or bending, a certain minimum amount of creep or hysteresis is unavoidable, this amount depending upon the physical constants of the material and upon the time involved in the cycle. The volume changes involved in shear or torsional stressing are very much smaller, and the unavoidable thermal creep is therefore much less. Second, these facts indicate that to obtain the maximum theoretical benefit from experimental studies of creep or hysteresis, the amount and speed of this thermal creep should be computed or estimated and if appreciable deducted from the measured creep, so enabling studies to be made of the characteristics of the plastic or pseudo-elastic creep uncomplicated by the effect of the thermal creep.

To experimenters interested in accurate strain measurements, the existence of this thermal creep indicates the need of a careful time schedule of measurements if reproducible results are to be obtained. A notable illustration of this occurs in the case of the use of elastic devices for the calibration of testing machines. Due to the thermal creep alone, maximum errors of 0.2 per cent (in steel) are possible, a figure which is sufficiently close to the accuracy desired in calibration as not to be negligible. This can largely be eliminated by placing the calibrating device in a cyclical state, then loading, and waiting a specified time after loading before reading. This time should be great enough to avoid the initial phase of rapid equalization of temperature which would occur in thin or small cross-sections, but not long enough to introduce more than a minimum amount of the pseudo-elastic creep which except under ideal conditions is likely to be simultaneously present. Present specifications call for placing the calibrating device in a cyclical state, but do not adequately cover the question of time limits, which is equally important.

It may be well to give an idea of the actual magnitude of these factors. The decrease in temperature in a given steel wire for a tensile stress increase of 10,000 lb. per sq. in. would be, for example, 0.104° F. (0.058° C.). When hanging vertically in still air, the rate of heat loss from this 0.028-in. diameter wire by conduction and convection to the surrounding air would be such that the temperature differential would be halved each succeeding 13 seconds. For other diameters, the time required for a given per cent temperature equalization will vary approximately as the diameter. Thus a rod 0.28 in. in diameter would undergo half of its total thermal creep in the first 130 seconds. With larger sizes, two other factors become important, one the decrease in temperature differential from surface of bar to surrounding air due to the development of temperature gradients within the bar, and the second the rate of heat loss by conduction from the center of the bar into and through the end grips.

In the case of bending, temperature differentials will develop of the same general magnitude as just indicated. Equalization will occur both by conduction from regions of compressive to regions of tensile stress, and from the surface skin of the specimen to the surrounding air. Considering only the rate of conduction through the metal, the time required to cut the temperature differential in half, and so to allow the first half of the total thermal creep to occur in steel, is approximately 10 b^2 seconds, where b is the depth of the piece, or the distance between points of maximum tension and compression, measured in inches.

THERMAL EFFECTS IN PLASTIC FLOW

When stressing beyond the elastic limit, all the thermal phenomena already mentioned continue. In addition, there are added the thermal effects due to the absorption of energy in plastic flow, which of course always results in increase of temperature. The point to be here emphasized is not the existence of this thermal effect, but rather the way in which this thermal effect is momentarily localized and the influence which this has both upon the theory of flow and upon the practical technique of testing in cases of plastic flow.

Take for example the case of a steel bar which under a tensile load of 35,000 lb. per sq. in. undergoes a plastic elongation of 0.001 in. per inch. The energy absorbed in plastic flow is 35 in-lb. per cu. in., enough to raise the temperature of this cubic inch of steel by 0.116° F. (0.064° C.). This is apparently a negligible amount. It is, for example, much smaller than the drop in temperature which would accompany an elastic elongation of the same relative amount (0.001 in. per inch elastic elongation is equivalent to a stress change of approximately 30,000 lb. per sq. in., which would cause a temperature drop of 0.312° F. (0.174° C.)). On the other hand, it must be noted that this plastic slippage has not been evenly distributed over the entire volume of the material, but has been concentrated on a series of slip planes, placed in general at angles more or less approximating 45 deg. to the length of the bar. Assuming for the moment an average slip distance of 100 atoms along each slip plane, the average spacing of the slip planes would necessarily be 70,000 atoms. Each slip occurs rapidly, and momentarily the resulting energy would be concentrated within a thin layer a few atoms thick on each side of the slip plane, or rather at those places along the slip plane at which major resistance had occurred. In other words, only a minute fraction of the total volume is affected, and the energy liberated within this minute fraction is sufficient to cause molecular agitation equivalent to rises in temperature of several thousand times the average rise of 0.116° F. already mentioned. An analogous case is the surface rise in temperature in cases of dry friction, which apparently may reach hundreds of degrees even when there is no noticeable rise in temperature in the mass of the metal as a whole.

Depending upon the initial temperature of the metal, the speed at which each individual slip occurs as compared to the rate of heat conduction within the material, the unit stress at which the deformation occurs, and the heating or cooling effect of adjacent dies or grips, these localized temperatures may or may not rise high enough to greatly exceed the critical temperature of the metal. The rate of cooling by conduction to the adjoining metal and so the degree of hardening due to incipient recrystallization as these overheated areas rapidly cool, will also be affected by much the same factors. Upon these two considerations will probably in large measure depend the behavior of the material.

No attempt will be made to follow further the possible theoretical conclusions which may be drawn from this statement. It is brought up here only to emphasize the fact that success in any investigations of plastic flow, as for example in studies of the pressing qualities of thin sheet, is likely to hinge on more careful control both of temperature and speed factors than has been customary in experimental work in the past and to suggest that more attention be centered on these factors.

REFERENCES

(1) Lord Kelvin, "Mathematical and Physical Papers," Vol. 1, p. 291.

Original statement of theory for temperature changes in elastic extension.

(2) J. P. Joule, "Scientific Papers," p. 413.

Extension of Lord Kelvin's Theory, with experimental verification.

(3) W. Voigt, "Thermodynamik," Vol. 1, p. 300 (1903).

Derivation of equations for temperature changes in elastic deformation in tension, compression, bending and torsion.

(4) Anton Wassmuth, "Über die Bestimung der thermischen Änderungen der Elastizitats konstanten isotroper Körper aus den Temperaturänderungen bei der Drillung und der gleichformiger Biegung," Boltzmann Festschrift, p. 555 (1904).

Restatement of Voigt's equations.

(5) K. T. Compton and D. B. Webster, "Temperature Changes Accompanying the Adiabatic Compression of Steel," *Physical Review*, Vol. 5, p. 159 (1915).

Gives experimental results which show astonishingly close agreement with theoretical values.

(6) W. S. Farren and G. I. Taylor, "The Heat Developed During Plastic Extension of Metals," *Proceedings*, Royal Soc. London, Series A, Vol. 107, p. 423 (1925).

Experimental values for temperature changes in plastic extension, showing that the observed evolution of heat would account for 86 to 95 per cent of the thermal equivalent of the work done in the steel, copper and aluminum samples tested.

(7) T. R. Lawson and J. A. Capp, "Thermoelectric Indication of Strain as a Testing Method," *Proceedings*, Internat. Assn. Testing Mats., Section IX_8 (1912).

Use of temperature changes in elastic and plastic extension as an indicator of moment of first plastic elongation.

DISCUSSION

Mr. A. Nadai[1] (*presented in written form*).—In his recent investigations on the elastic after-effect in metals,[2] Mr. Sayre brings this effect in connection with the slight changes of the temperature of thin metallic bars which are observed in such bars after loading or unloading them suddenly in tension. The writer, having learned in a conversation with Mr. Sayre some time ago about some of these after-effects observed in extension tests made with long wires tested in a 50-ft. long pipe held in a vertical position, is pleased to see that a probable or possible reason for some special after-effects has now been advanced by Mr. Sayre—at least perhaps in part to explain some of his observations as far as they refer to long and thin wires.

In extension experiments made with a comparatively long thin wire in air (or a liquid) loaded rapidly by a weight or unloaded rapidly, the Joule-Kelvin effect may indeed produce after-effects in the right sense. If a steel wire is rapidly loaded in tension, the temperature is found to decrease by a small amount. The wire suddenly becoming a little colder than the surrounding medium will have to take heat on from the surrounding atmosphere and therefore will lengthen further due to the thermal expansion corresponding to the slight subsequent rise of its temperature to the temperature of the air. The writer can, however, not quite see that the same reason might also explain in general the elastic after-effect, or even larger parts of it, if instead of long wires comparatively short and compact steel bars are subjected to tension. The steel bar being a good heat conductor and having heads in connection with additional masses (heads, grips) which compared to the mass of the test bar are large and consist also of a good heat conductor—will keep the slight change of the temperature only for a comparatively short time. If the loading or unloading is not done *rapidly* (or the bar is not insulated from surrounding masses against heat exchange) in short bars the slight changes in temperature will die down rapidly. A short steel bar will take on heat or release heat from or to the grips in a short time. The elastic after-effects might, however, still show up (depending on material properties) after considerable time has passed, sufficient to equalize all possible temperature differences which might have existed due to the Joule-Kelvin effect.

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[1] Research Engineer, Westinghouse Electric and Manufacturing Co., East Pittsburgh, Pa.

[2] See also paper by M. F. Sayre, presented before the meeting of the Society of Rheology in December, 1931, in Rochester, N. Y.

The writer had occasion to observe these and a number of other or similar thermoelastic effects in tests made twenty years ago.[1] The slight temperature changes due to sudden application of loads were observed in elastic tension, compression and bending tests. The heat generated through yielding was also clearly shown. Although the slight thermal effects could well be detected (for example, a bar subjected to sudden bending was found to become slightly colder on the tension and slightly warmer on the compression side) the impression of the writer was that most of these effects are probably only of a secondary importance to engineers or for extension tests on account of the rapid heat exchange in a good heat conductor. The exceptionally long wires with which Mr. Sayre experimented may perhaps be such a case, where these slight thermal effects may show up in the readings of an extensometer.

Mr. Sayre speaks of additional thermal effects "due to absorption of energy in plastic flow." According to careful tests made by W. Hort[2] and by G. J. Taylor, only a comparatively small percentage of energy was found absorbed by a steel bar when cold worked. Most of the work of plastic deformation in a steel bar is changed in the equivalent amount of heat, an energy which perhaps should not be termed as "absorbed," but rather generated or transformed into heat.

The writer cannot agree to Mr. Sayre's statement, that the so-called elastic after-effect and also elastic hysteresis is in part at least due to the purely thermal cause quoted in the paper and independent entirely of any defects in elastic behavior in the material itself. It suffices to mention, for example, the elastic hysteresis of such materials as cast iron (which show pronounced loops) to see that the elastic hysteresis has nothing to do with thermal effects of the kind mentioned by Mr. Sayre, but is primarily due to a friction phenomenon, occurring because of the soft graphite particles or inclusions—or to the presence of imperfections in the material.

Mr. L. B. Tuckerman[3] (*presented in written form*).—Mr. Sayre's paper will serve a very useful purpose in calling the attention of engineers to the need of considering thermal effects where they are of importance in accurate elastic and plastic measurements. There is no question that these effects are of great importance in accurate studies of mechanical hysteresis, drift, creep and plastic flow. These effects have been overlooked by many persons who have published studies in these fields.

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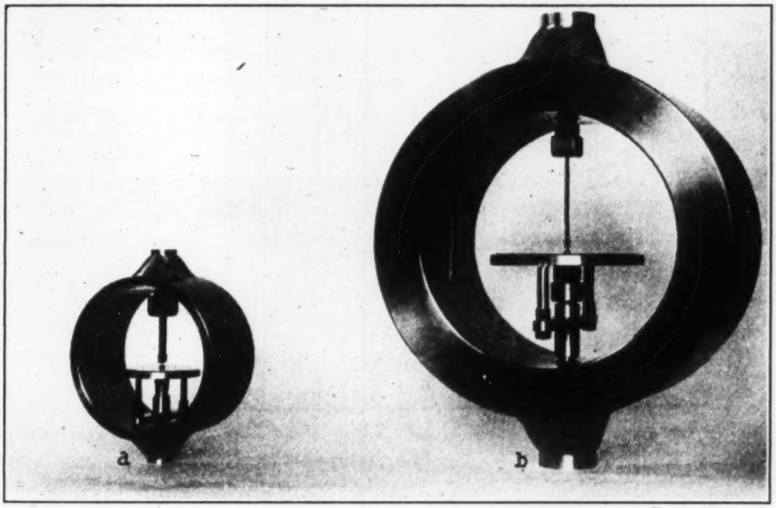
[1] "Untersuchungen der Festigkeitslehre mit Hilfe des thermoelektrischen Temperaturemessverfahrens," Dissertation, Technische Hochschule, Berlin (1911).

[2] "Die Wärme vorgänge beim Längen von Metallen." *Forschungshefte*, Verein Deutscher Ingenieure, No. 41 (1907).

[3] Assistant Chief, Division of Mechanics and Sound, U. S. Bureau of Standards, Washington, D. C.

However, I feel that some parts of the paper are likely to leave an erroneous impression concerning the use of elastic devices in measuring and especially in calibrating testing machines. It seems to me very important that engineers do not become unjustly suspicious of properly made elastic calibrating and measuring devices since they serve a purpose that at present no other devices can serve. It seems to me also important that they should not gain the impression that especially elaborate precautions are necessary to secure accurate results from their use. No necessary precautions should be omitted, but every unnecessary precaution adds to the cost of the procedure and discourages its use.



(a) Capacity 10,000 lb. (b) Capacity 300,000 lb.

FIG. 1.—Whittemore-Petrenko Proving Rings, Manufactured by the Morehouse Machine Co.

In several places in his discussion, Mr. Sayre implies[1] that it is necessary to specify close time schedules in the use of elastic calibrating devices if errors of the order of 0.2 per cent caused by elastic after-effects and thermal creep are to be avoided. As I shall show later, in all well-made practical elastic calibrating devices which depend upon bending for their action, such refinement is unnecessary.

At the U. S. Bureau of Standards we are particularly interested in this question because of its relation to the calibration of testing machines by elastic devices. We believe that testing machines should be calibrated at regular intervals and, so far as practical means are available, over their whole range. If this is to be done, sufficiently accurate and sufficiently convenient calibrating devices must be available. So far as we can see now, elastic calibrating devices offer the most practical solution. If they are to be used as freely as is desirable, it is important that their use be hedged about with no more complications than are absolutely necessary.

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[1] See p. 584, line 12; p. 585, line 24; p. 590, lines 7 and 39.

The Society's Standard Method of Verification of Testing Machines (E 4 – 27),[1] sets the limit of error of a new testing machine inside its loading range at 1 per cent. Experience in standardizing laboratories has shown that the limits of error in a calibrating device, should, wherever practical, be no greater than one-tenth the error tolerated in the device to be calibrated. For this reason U. S. Bureau of Standards *Letter Circular No. 294*, "Specifications for Proving Rings for Calibrating Testing Machines," specifies:

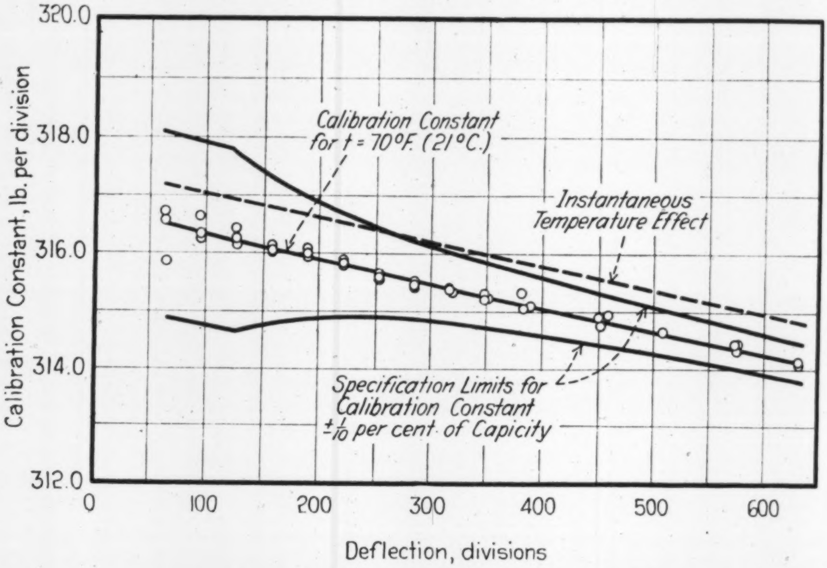

FIG. 2.—Typical Calibration Curve of a Proving Ring.

> 5. (*b*) *Range $\frac{2}{10}$ to Capacity Load.*—The observed deflection of the ring, for any applied load not less than two-tenths nor exceeding the capacity load, shall not differ from the average of a number of successive observations for the same applied load by more than one-tenth of one per cent of the deflection for the capacity load.

These limits of error are below the error (0.22 per cent) which can theoretically be caused by thermal creep in steel. It is therefore a matter of real importance to know what precautions, if any, are necessary to prevent these effects from affecting measurements with elastic calibrating devices.

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[1] 1930 Book of A.S.T.M. Standards, Part I, p. 914; also Part II, p. 1123.

At the Bureau of Standards our largest experience with elastic calibrating devices has been with proving rings manufactured by the Morehouse Machine Co. which are based on the principles of construction first worked out by Whittemore and Petrenko at the Bureau of Standards. These rings range from 2000 to 300,000 lb. in capacity. (Fig. 1.) All of those manufactured and sold by the Morehouse Machine Co. have been tested at the Bureau of Standards and certified to meet this specification. As a matter of fact they average somewhat better. Over most of the range the error seldom exceeds 0.05 per cent, as can be seen from the accompanying typical calibration curve obtained by loading a ring with dead weights up to 100,000 lb. (Fig. 2.) On this curve a dotted line has been drawn to show the magnitude of the thermal creep which should theoretically be present in these rings. Some of these rings owned by the Bureau of Standards have been boxed and shipped repeatedly and disassembled and reassembled more than once, calibrations being made after any unusual treatment. None of the repeated calibrations showed any individual reading lying outside of the specified tolerances. Except in the case of the 300,000-lb. rings recently purchased no precautions were taken either in calibrating or in using these rings to avoid errors caused by thermal creep, nor have we written into the "Instructions for use," which are included in U.S. Bureau of Standards *Letter Circular No. 294*, any prescription of time limits for taking readings. We felt sure they were not necessary and our experience seemed to justify us. In the 300,000-lb. rings which we have just recently bought a slight lag has, for the first time in our experience, been noticed when a large load was put on or released. With these rings we adopted the obvious expedient of waiting a minute before starting readings.

Although we have felt sure that the rather summary consideration we gave to thermal creep some years ago when Whittemore and Petrenko first started their experiments on proving rings had been sufficient to show that it did not necessitate any elaborate precautions in the accurate use of proving rings, Mr. Sayre's paper has made it seem desirable to go into the matter somewhat more thoroughly.

Since the nomenclature of departures from "pure elastic action" in elastic bodies has not been standardized, I shall define the terms which I use to describe those departures which limit the accuracy of elastic measuring devices before I discuss them:

1. *Elastic Drift.*—A limited increase with time of the deformation of an elastic structure under a constant applied load. The rate of increase approaches zero asymptotically.
2. *Elastic Recovery.*—The complement of elastic drift. The asymptotic approach with time of an elastic structure deformed under load to its undeformed condition after the removal of load.

These are by definition both self limited effects. In practice they are sometimes not distinguished from "thermal creep" as defined by Sayre.

> 3. *Elastic Creep.*—The progressive slow increase with time of the deformation of an elastic structure under a constant applied load, smaller than would be necessary to produce plastic yield.
> 4. *Set.*—A permanent deformation remaining in an elastic structure after removal of load.

Elastic Creep as distinguished from *elastic drift* is not self limited and always results in *set* after removal of the load which produced it. *Elastic creep* as here defined passes progressively into plastic yield as the load is increased.

We have provided in the proving ring specification against errors caused by these effects by the following clause:

> 4. *Overload.*—The ring shall be overloaded repeatedly to a load of 10 per cent more than its capacity load. The difference between the zero load reading after the first overload and the zero load reading after any subsequent overload shall not exceed one-tenth of one per cent of the deflection of the ring under capacity load.

This obviously eliminates appreciable set under normal load and should therefore insure that elastic creep is not appreciable. It does not so obviously eliminate appreciable drift. However, the elastic recovery observed in the 10 per cent overload tests that we have made on the Morehouse rings has seldom exceeded 0.1 per cent and then only by amounts approximating the experimental error of reading, $\frac{1}{10}$ division on the dial.

We feel sure therefore that elastic proving rings meeting these specifications will not under normal loading need any special time limits to avoid appreciable errors caused by elastic creep or elastic drift.

This opinion is strengthened by our experience in calibrating over 100 Morehouse rings which met these specifications. It is further strengthened by the success of the Aeronautic Instruments Section of the Bureau (in cooperation with the Bureau of Aeronautics of the Navy) in the far more difficult task of specifying material performance for the small elastic members used in aeronautic instruments which has in large measure eliminated the elastic drift and creep which used to be so troublesome in these instruments.

> 5. *Static Hysteresis.*—The difference in deformation of an elastic structure when the same load is applied at different stages in a load cycle.

Static hysteresis is, as its name implies, independent of the time rate of loading and depends only on the sequence of loads in the load cycle. Even in materials which show negligible elastic creep and drift in the cyclic state, the static hysteresis may be appreciable.

No matter how carefully the materials are chosen it cannot be safely ignored in any elastic measuring or calibrating device from which accuracies of the order of 0.1 per cent are desired.

Static hysteresis is provided for in the specifications for proving rings by the following clauses:

> III. 2. Before using a proving ring for a calibration, preload it by applying and removing the greatest load which is to be used in the calibration. This preloading is especially important if the ring is used for both tensile and compressive loads.
>
> III. 5. . . . Note: Proving rings, like all elastic bodies do not have identical calibration constants for increasing and decreasing loads. They will be calibrated under increasing loads unless it is specifically requested that they be calibrated under decreasing loads. If both are desired they will be considered as two separate calibrations.

There remains only the question of "thermal creep" as defined by Mr. Sayre. This effect is undoubtedly of importance in any large tension or compression calibration bar from which accuracies of 0.1 per cent are desired. However, in devices using bending or torsion the temperature equalization is much more rapid and the question of its practical importance becomes a question of how long it takes for the temperature difference to equalize.

Mr. Sayre gives the approximate value of $10\,b^2$ (in.^{2}) seconds [$1.55\,b^2$ (cm.^{2}) seconds] as the half-creep time of the thermal creep for a steel bar suddenly bent. We are unable to check this value. For any given steel, the half-creep time will of course vary somewhat with the shape of the bar, but for all practical purposes we can limit the discussion to the simplest case of a rectangular bar. From the usual Fourier Series[1] the equation for the half-creep time (t) of an insulated rectangular bar with a linear initial temperature distribution (a sufficiently close approximation to the suddenly bent bar) can be written:

$$\tfrac{1}{2} = 1 - \frac{8}{\pi^2} \sum_{0}^{\infty} \frac{1}{(2n+1)^2} e^{-(2n+1)^2 u}$$

$$t = \frac{b^2}{a^2\pi^2} u$$

$$a^2 = \frac{k}{sd}$$

where k = thermal conductivity of the material,
s = heat capacity of the material,
d = density of the material, and
b = thickness of the bar.

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[1] Byerly, "Fourier's Series and Spherical Harmonics," p. 106, Ginn and Co., Boston (1893).

a and u are auxiliary symbols introduced for convenience. The solution of this equation is, to three significant figures, $u = 0.485$. Strictly speaking this equation does not represent the rate of thermal creep of the elastic deformation of the bar but the rate of decrease of the temperature difference between the two surfaces. The temperature distribution is at first nearly linear but approaches asymptotically to a sine distribution as the temperature difference of the surfaces approaches asymptotically to zero. This is illustrated in Fig. 3 drawn to illustrate the conditions in a 2000-lb. ring on the assumption:

$$a^2 = 0.1 \frac{\text{cm.}^2}{\text{sec.}}$$

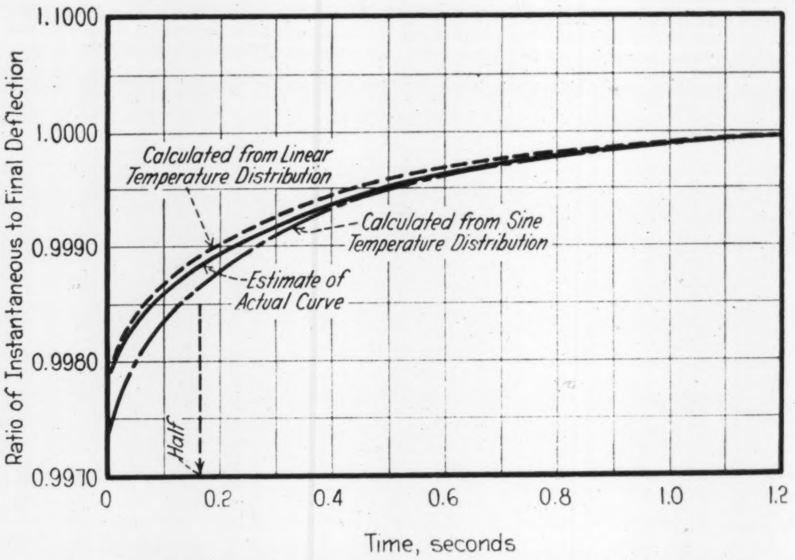

FIG. 3.—Theoretical Time Lag for a 2000-lb. Capacity Proving Ring.

The upper curve represents the curve of approach of the surface temperatures to equilibrium. If the temperature distribution remained linear it would also represent the curve of thermal creep. The lower curve is the curve of thermal creep for an initial sine distribution of temperature, which would of course continue a sine distribution during the process of temperature equalization. The actual curve of thermal creep under the assumed conditions would lie somewhere between these two curves as shown by the solid line. This third curve was drawn in free hand by guess, as it was not worth while to carry out the elaborate calculations necessary to determine it more accurately.

The ring is not a bar and its surfaces are not insulated, so that temperature equalization can take place along the ring and into the surrounding air as well as across the ring as assumed in the theory. These effects would tend to shift all of the curves upward. a^2 will be different for each ring depending upon the chemical composition and previous treatment of the ring. Higher values of a^2 would shift all the curves to the left, lower values to the right. The most we can so far say definitely is that the curve shows the order of magnitude of the time necessary for the thermal creep to disappear. It may be noted that the half-creep time calculated for these 2000-lb. rings is about 0.16 seconds, far too short for the thermal creep to be noticed in any ordinary calibration.

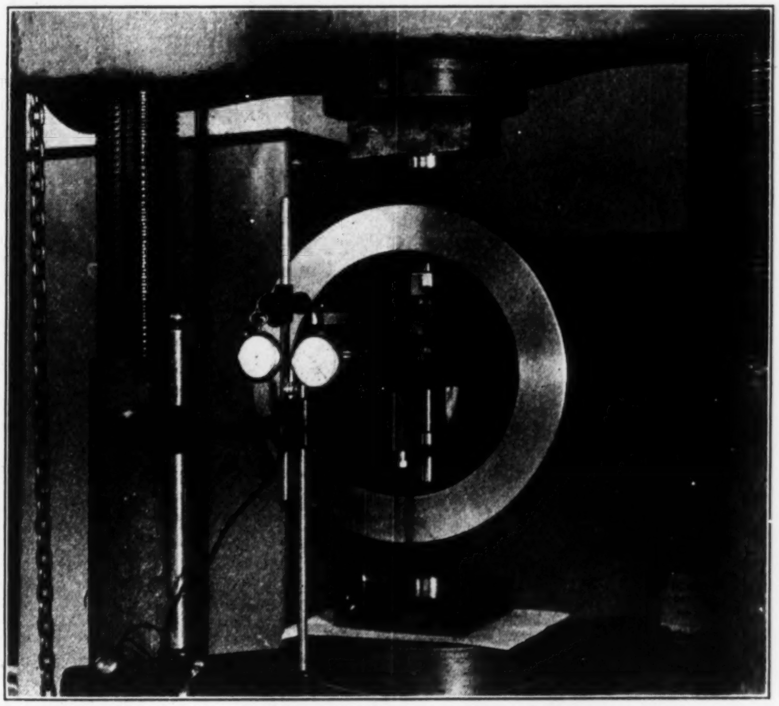

FIG. 4.—Experimental Set-Up for Measuring Time Lag of "Thermal Creep" on a 300,000-lb. Capacity Proving Ring.

Sayre's factor $1.55 \frac{\text{sec.}}{\text{cm.}^2} \left(10 \frac{\text{sec.}}{\text{in.}^2}\right)$ should represent approximately the factor $\frac{u}{a^2\pi^2} = \frac{0.485}{9.8696\, a^2}$ which gives $a^2 = \frac{0.485}{9.8696 \times 1.55}$ $= 0.0317 \frac{\text{cm.}^2}{\text{sec.}}$

In the work at the Bureau of Standards where it is not thought worth while to determine an accurate value for a particular specimen of steel, it is customary to assume $a^2 = 0.1 \frac{\text{cm.}^2}{\text{sec.}}$ as a convenient and sufficiently accurate value for the ordinary carbon and low-alloy steels.

The largest value for the specific heat (k) of these steels at ordinary temperatures which I find is $0.12 \frac{\text{calories,}}{\text{g., deg. Cent.}}$, the largest value for the density 7.9 g. per. cu. cm., from which:

$$k \not> 0.948\, a^2 \frac{\text{calories}}{\text{cm., sec., deg. Cent.}}$$

For the usual carbon and alloy steels, k is usually in the neighborhood of $0.1 \frac{\text{calories}}{\text{cm., sec., deg. Cent.}}$ and only for high percentages of alloying material does it fall much lower (for example 10 per cent nickel, k = about 0.05). Sayre's value 10 b^2 (in.^{2}) seconds of the half-creep time would require a value of $k \not> 0.03 \frac{\text{calories}}{\text{cm., sec., deg. Cent.}}$

TABLE I.—MOREHOUSE MACHINE COMPANY'S THERMAL LAG OF PROVING RINGS.

CAPACITY, LB.	HALF-CREEP TIME, SECONDS	THREE-QUARTERS-CREEP TIME, SECONDS
2 000	0.2	0.4
6 614	0.3	0.8
10 000	0.5	1.1
25 000	1.0	2.4
50 000	2.0	4.9
100 000	4.0	9.8
200 000	8.1	19.6
300 000	13.5	32.8

In our judgment, a better rough approximation to the half-creep time of the thermal creep of the usual measuring device using the elastic bending of steel would be 3 b^2 (in.^{2}) seconds. From a practical standpoint the three-quarter creep time would be more convenient for use with bent steel measuring devices where a limit of accuracy of 0.1 per cent was desired. This would reduce the creep effect below 0.05 per cent or sufficient to be surely negligible. On the basis of $a^2 = 0.1 \frac{\text{cm.}^2}{\text{sec.}}$ the values of the half-creep and three-quarters-creep time for Morehouse rings of different capacities are given in Table I.

There was sufficient uncertainty in the reasoning by which this value of a^2 was secured that we thought it worth while to make an experimental check.

The slight effects observed on the 300,000-lb. rings gave the hope that with the aid of a moving picture machine we might really get some measurements of the thermal creep before it had disappeared. We therefore replaced the vibrating reed and micrometer screw in one of these rings by the device shown in Fig. 4. This consisted of a stop watch, a Last Word dial, mounted on a 10 to 1, flexure plate, multiplying lever and a miniature incandescent lamp. The whole was mounted in a Southwark Emery testing machine which we could unload more rapidly than any other machine in our laboratory. The lamp was turned on the instant the release valve was opened and automatically went out when the head of the testing machine lifted from the ring (zero load). The moving picture camera recorded the initial zero reading and was started again just before the release valve was opened, recording simultaneously the lighting of the lamp and the reading of the stop watch and the dial. The load of 300,000 lb. was applied in about three-quarter minute and held on for about half a minute. It took 4 seconds for the load to drop to zero. The results are shown in Fig. 5. A second run gave results which could not be clearly separated on the figure from the observed points shown.

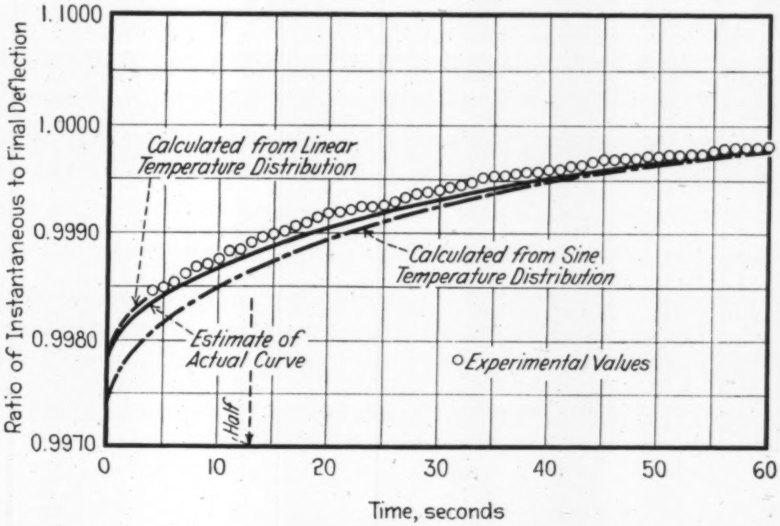

FIG. 5.—Comparison of Theoretical and Experimental Time Lag of "Thermal Creep" on a 300,000-lb. Capacity Proving Ring.

The observed points represent of course the combined effect of thermal creep and whatever elastic drift may have been present. They show that the values of half-creep time and three-quarters-creep time given in Table I are a sufficiently close approximation for all practical purposes.

In conclusion we may say:

The effects Mr. Sayre mentions are all present in elastic measuring and calibrating devices, but not of so great practical importance as might be inferred from his paper.

In elastic devices of suitable design and suitable materials, elastic drift and elastic creep can be made negligible. They are negligible in proving rings meeting Bureau of Standards specifications.

Static hysteresis cannot safely be ignored in elastic measuring or calibrating devices from which accuracies of 0.1 per cent are desired. Its effects can, however, be provided for by putting the device in a proper cyclic state. This is, as Mr. Sayre has noted, provided for in the specifications for the use of elastic calibrating devices.

Thermal creep should be carefully considered in the use of elastic calibration devices stressed in tension or compression alone if accuracies of the order of 0.1 per cent are desired.

Thermal creep in devices depending upon torsion or bending for their action vanishes very rapidly. In the proving rings of largest capacity so far constructed the effect practically disappears in less than a minute. Personally, I should, for entirely different reasons, place little confidence in a calibration of a testing machine, if a reading were so hurriedly taken as to be completed and checked in so short a time.

Finally, proving rings built to meet proper specifications have shown themselves constant and reliable, needing no greater precautions in their use than should be given to any accurate instrument.

MR. M. F. SAYRE.[1]—I thoroughly agree with Mr. Tuckerman that there is no reason to fear the accuracy of elastic calibrating devices when properly used. In fact, I have recently in connection with some other work, been carrying on studies of elastic calibrating devices where we were interested in accuracies—not of a 0.1 per cent but of a 0.01 per cent, and where we were obtaining in the main these accuracies. My suggestion regarding elastic calibrating devices was a general one, intended to apply particularly to those persons using them who were not as familiar with their proper use as the people at the Bureau of Standards, for example. In fact, as Mr. Tuckerman has said, the precautions necessary in the case of elastic calibration devices dependent primarily upon bending for their action may be no more than would naturally and more or less automatically be taken by personnel such as that at the Bureau of Standards: namely, to wait the short time necessary for the initial "creep" period to be over, and then to take readings without undue delay. It would, however, still be advisable to insert such recommendations in instructions of a general type.

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[1] Associate Professor of Applied Mechanics, Union College, Schenectady, N. Y.

In tension or compression devices such as elastic calibration bars, more elaborate instructions would be necessary. In moderate to large sized bars such as would be used for this purpose, temperature equalization will occur less rapidly than in the cases of bending or of long thin wires in tension (not more rapidly, as suggested by Mr. Nadai). The same general time schedule should therefore be adhered to when using these bars for calibration as when originally calibrating the bars.

Mr. Tuckerman has stated that thermal creep in devices depending upon torsion or bending for their action vanishes very rapidly. I will go a bit further than this statement. In bending devices the thermal equalization occurs rapidly, but not so rapidly but that observers will do well to be on their guard against it. In torsion devices, such as helical springs, the thermal equalization does not occur at all, because it is not necessary. This particular thermal effect hinges upon the existence of volume changes such as occur in bending or direct tension or compression, but which are virtually absent in torsional stress. As concerns the thermal creep in bending, the data given by Mr. Tuckerman for the amount of this creep in proving rings as measured is truly a very satisfactory proof of the theory as derived. I think that a statement made verbally by Mr. H. F. Moore regarding the measurements made on the 1½-in. bar of steel, in which the effect was very definitely observed, probably answers Mr. Nadai's comments regarding the probability that the effect would be evident in a small wire in tension and much less evident in a large bar. I should expect that in a large bar it would probably be more evident because the time of equalization would be longer than in the case of the wire with which we were working.

Mr. Tuckerman's remarks regarding the speed with which temperature equalization occurs following bending are pertinent. My own figure of 10 b^2 seconds was based on very rough approximations and I am glad to have his corrected figure of 3 b^2 seconds. Incidentally, this change, while reducing the importance of this thermal effect in proving rings, indicates that it is more important than I had first expected, as a cause of energy absorption in small revolving shafts.

Another point: I should not like to be misunderstood as suggesting that this thermal effect is adequate as a complete explanation for the observed "elastic" after-effects. I think the evidence is very strong indeed, that except possibly in isolated cases we shall have present both this thermal effect and also a genuine elastic or pseudo-elastic effect. The relative magnitude of the two will differ in different cases. In carefully heat-treated spring steels, for example, our tests have shown that a very large percentage of the apparent creep which occurs during the first few minutes after loading can be accounted for by this thermal cause. Various published reports on creep investigations have entirely failed to take this into account. On the other hand, the total elastic hysteresis in such materials as cast iron is of such magnitude that the thermal component would be of very small comparative magnitude. It would still, of course, be present.

I hesitate to make as sharp a distinction as Mr. Tuckerman makes between elastic drift and recovery and elastic creep. The definition given by him of elastic drift: "A limited increase with time of the deformation of an elastic structure under a constant applied load. The rate of increase approaches zero asymptotically," suggests that the rate of decrease may be relatively rapid, and similarly that in elastic recovery, the approach to original conditions will be equally rapid. In our tests on wire, the elastic recovery, after a wire has been loaded for any appreciable period of time, extends over a very long period and is frequently not completed at the end of 24 hours. It will continue beyond that, I know, up to 3 days. How much longer I do not know. We still have a great deal to learn about these elastic effects. I have been worrying my head for two or three years to find out what the difference was between elastic effect, plastic effect and pseudo-elastic effect, and I confess I still know very little about it.

MEASUREMENT OF PARTICLE SIZE WITH AN ACCURATE AIR ANALYZER: THE FINENESS AND PARTICLE SIZE DISTRIBUTION OF PORTLAND CEMENT[1]

By P. S. Roller[2]

Synopsis

A number of improvements have been made in an apparatus previously described for determining the particle-size distribution of a fine powder by air separation and weighing of the fractions. The essential new feature of this apparatus is that a U-container undergoes constrained oscillations in such manner that the charge of powder is continuously brought into effective contact with the air jet by undergoing a combined translatory and rotatory motion.

Analysis into fractions 0 to 5, 5 to 10, 10 to 20, 20 to 40, 40 to 80, and 80 to (160) microns has been made of four brands of portland cement and of three laboratory ground clinkers. It is found that the deviation of the recorded percentages by weight is nearly the same for all the fractions and averages close to ±0.2 per cent. The time required for fractionation varies from 62 minutes for the 0 to 5-micron to 11 minutes for the 40 to 80-micron fraction; for the six fractions the average total time of separation is less than three hours.

A rapid and efficacious method is described of preparing a fine powder for microscopic examination by using a thin platinum wire and a drop of 0.25 per cent solution of saponin in 50-per-cent alcohol.

It is shown that the distribution of particle sizes in each fraction is closely within the theoretical limits given by Stokes' law and that the mean diameter may be taken as the theoretical mean of the Stokes' law limits. The surface mean diameter and the dispersion of the cements are calculated, and the results for the percentage by weight in each fraction are plotted so that the area under the curve represents the surface area of the cement powder contained between any two particle sizes. From this curve it is deduced that grinding selectively segregates the chemical constituents of a portland cement into two major particle-size categories.

For the size analysis of powders substantially passing through the No. 200 mesh sieve and composed of microscopic particles essentially 1 to 100 microns in size, a new type of air analyzer was previously described[3] and preliminary experimental results were recorded with two or three materials. A number of improvements have since

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[1] Publication approved by the Director of the Bureau of Mines of the U. S. Department of Commerce.

[2] Associate Chemist, U. S. Bureau of Mines, Nonmetallic Minerals Experiment Station, New Brunswick, N. J.

[3] P. S. Roller, U. S. Bureau of Mines *Technical Paper No. 490*, p. 1 (1931).

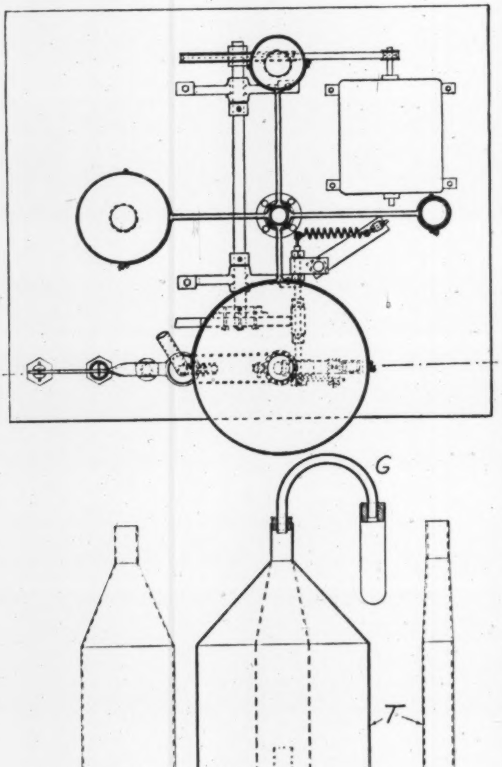
G
T
K
R
L
C
S"
A
S'
H

FIG. 1.—Air Analyzer Assembly.

been made in the design of the apparatus and in the manner of operation so as to facilitate the analysis and enhance the accuracy. In this paper are described the apparatus in its present improved form, and the method of operation; data on the analysis of several commercial portland cements and laboratory ground clinkers are presented and interpreted.

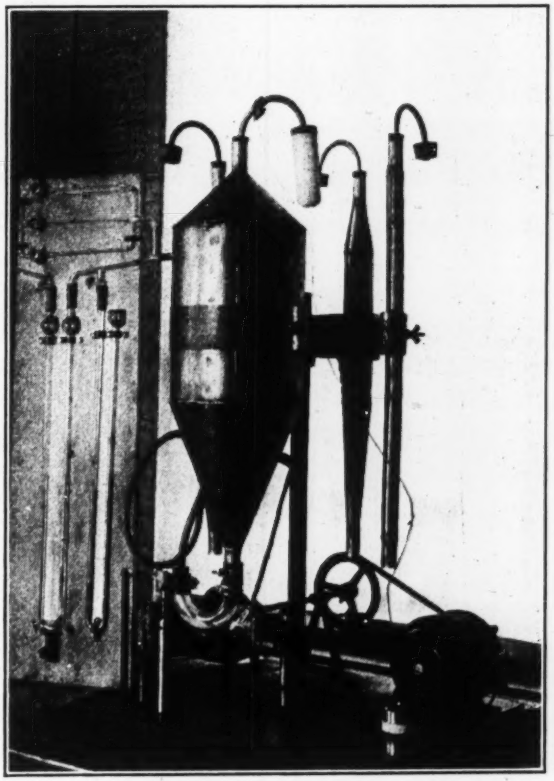

FIG. 2.—General View of Apparatus and Flowmeter.

DESCRIPTION OF APPARATUS

Referring to Figs. 1, 2 and 3, four vertical settling tubes, *T*, are mounted on a cast-aluminum bracket that can be rotated about a central post so as to bring the tubes successively into position with reference to U-container *C*. Tubes *T* are made of No. 22 gage stainless sheet steel highly polished on the inside. The cylindrical portion is in each case 1 ft. high, and respectively 9.0, 4.5, 2.25, and 1.125 in. in inside diameter. At the bottom the cylinders are tapered over the length of 10 in. to join with a short length of 1-in. stainless-steel tubing. At the top, the tubes are similarly tapered over a length of 4 in. to join with a second short piece of 1-in. steel tubing. Gooseneck *G* is bent out of $\frac{1}{2}$-in. soft stainless-steel tubing, polished on the inside. At the free end of the gooseneck is a machined rubber stopper on which fits a paper extraction thimble for filtering the fractions that are blown over and which is large-sized to minimize the back pressure. Both *T* and *G* are well grounded electrically.

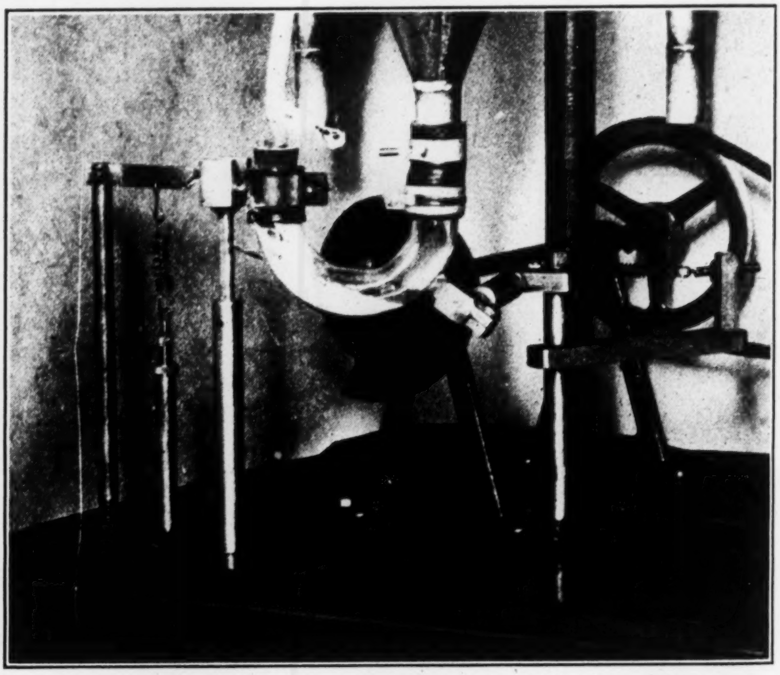

FIG. 3.—Close-up of U-Container, Leaf Spring Tapper Removed.

The powder charge, about 25 cc., is placed in U-container *C* made of heavy-walled Pyrex tubing, 1 in. in inside diameter, bent on a radius, with center located $\frac{5}{8}$ in. below the upper ends, of $2\frac{3}{8}$ in. from the center of the tube. At the right, U-container *C* is closely coupled to the reduced end of tube *T* by means of pure gum rubber tubing and hose clamps. At the left, a 7-mm. air inlet tube of chromium-plated brass is bent so that the air jet impinges on the bottom center of U-container *C* at an angle of about 30 deg. with the horizontal. The inlet tube is threaded on the inside so as to receive any desired nozzle size.

The rubber-tipped hammerhead of hammer *H* which causes U-container *C* to oscillate makes about 300 taps a minute and is actuated by a motor-driven fiber cam that operates upon a fiber roller on the hammer shaft. An adjustable tension spring *S′* controls the force of the hammer blow. On the return oscillation of the U-container lug *L* which is fixed to the left end of *C* strikes against abutment *A*. The latter is slotted to serve as a guide for *L* and is adjustable as to height. Arm *R* rests on *L* with a pressure that is determined by the strength of the adjustable tension spring S″. As illustrated in Figs. 2 and 3, the constrained oscillation of U-container *C* causes the powder charge to move as a whole in a direction opposite to the air jet, while the particles constituting the charge rotate in a clockwise direction so that fresh portions are continuously exposed to the action of the air. Adjustment to correct operation is obtained by altering the tension of springs *S′* and *S″* and adjusting the height of abutment *A* to bring U-container *C* to an approximately level position.

K in Fig. 1 is a five-leaf spring steel tapper about $\frac{3}{4}$ in. wide and $\frac{1}{32}$ in. thick that operates against the lower conical portion of the settling tubes *T*. This tapper profoundly affects the rate of separation, and also the uniformity of fractionation, by shaking down into container *C* particles which repose in the lower cone of the settling tubes. The wooden head at the upper end is weighted with an optimum quantity of lead (in this case about 20 g.) so as to give the strongest possible impact. At the lower end the tapper is mounted in such a way that it may be readily brought into position for a maximum blow or moved out of the way as the settling tubes are rotated into position. The mounting consists of an L-shaped bracket that can be rotated about the end of the shaft of hammer *H*. A threaded stud on the bracket projects through a slot in a sector plate that is fastened by a set screw to the hammer shaft. The bracket is held in position against the plate by means of a wing nut that screws on the bracket stud.

The calibrated flowmeter[1] consists of a bank of three capillaries 1, 2, and 4 mm. in inside diameter, each of which is associated with a wide-bore stopcock. In using a capillary the stopcock is adjusted for minimum difference of level in the arms of the flowmeter. The whole apparatus may be placed in a sound-proof chamber with hinged door, the motor being air-cooled or mounted externally.

THE END-POINT RATE OF SEPARATION

In the course of a separation, it is found that the particles that are blown over increase in size progressively upwards, as shown in Figs.

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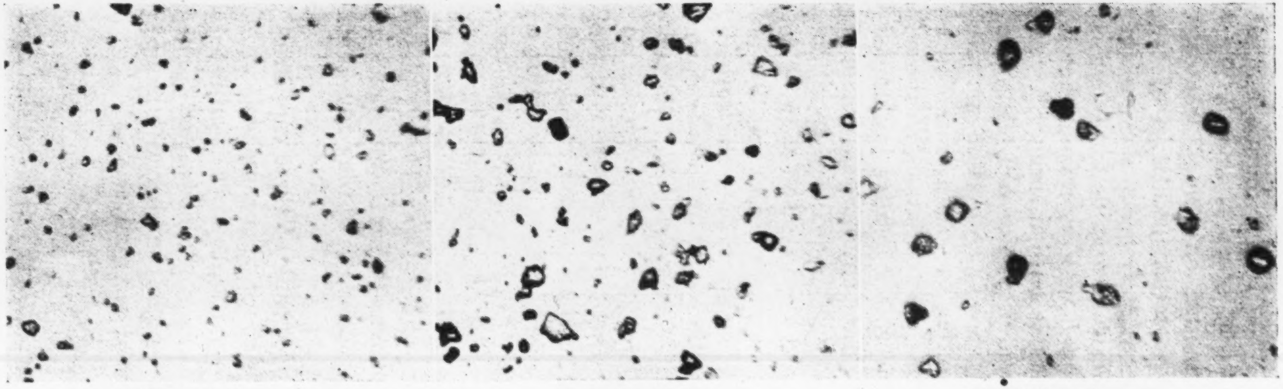
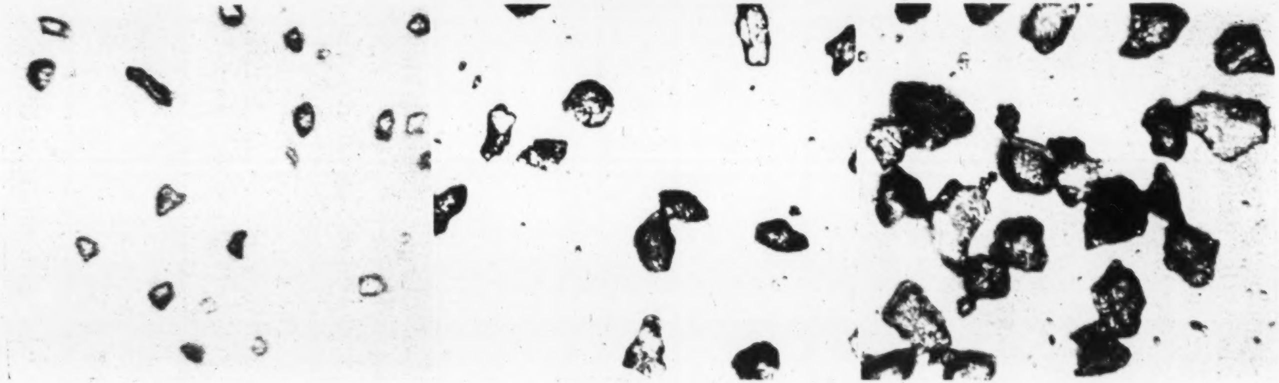
[1] P. S. Roller, U. S. Bureau of Mines *Technical Paper No. 490*, p. 1 (1931).



(*a*) First 25 minutes. (*b*) Second 20 minutes. (*c*) Third 20 minutes.

FIG. 4.—0 to 5-Micron Separation (× 650).



(*a*) First 2 minutes. (*b*) Second 18 minutes. (*c*) Third 22 minutes.

FIG. 5.—5 to 10-Micron Separation (× 650).

4 and 5 for the 0 to 5 and 5 to 10-micron separations. Eventually the particle sizes are almost wholly in the upper boundary of the fraction. In prolonging the separation beyond this point, the particle sizes increase beyond the upper theoretical limit, reaching a maximum of about 1.5 times the theoretical maximum particle size.

The reason for the oversize with prolonged fractionation appears to lie in the fact that in viscous flow such as obtains in the settling tube, the velocity distribution across the tube is not uniform but parabolic. From Poisseuille's law of flow, and also as experimentally observed,[1] the maximum velocity at the center of the settling tubes is twice the average velocity. This means that with prolonged fractionation the ultimate particles that are blown over are, as observed, $\sqrt{2}$ or 1.41 times the theoretical maximum calculated from Stokes' law.

TABLE I.—EFFECT OF NOZZLE SIZE ON PERCENTAGE IN 0 TO 5-MICRON FRACTION.

NOZZLE DIAMETER, d, MM.	$\frac{1}{d^2}$	BACK PRESSURE AT NOZZLE, INCHES OF MERCURY	PERCENTAGE BY WEIGHT IN FRACTION
7.00	0.021	....	5.62
3.05	0.106	....	9.62
2.08	0.23	0.2	10.60
1.75	0.33	0.5	10.54, 10.76, 10.86
1.45	0.48	1.0	11.50, 11.60
1.20	0.70	1.8	12.06, 12.22
1.04	0.93	4.0	11.76, 11.96, 12.54
0.96	1.08	5.0	12.44, 12.72
0.82	1.49	10.0	12.45, 13.20
0.76	1.73	12.0	12.96

In practice fractionation is completed at an end-point rate of separation at which the particles are in the upper theoretical boundary of the fraction. The end-point rate is determined empirically once for all by microscopic examination of the powder blown over and of the residue. For the same particle size separation, it appears to be proportional to the rate of air flow. In the present paper, the end-point rate of fractionation was found to be the same for all the fractions: 1.0 g. per hour. For a 100-per-cent variation in the end-point rate, that is from 1.0 to 2.0 or 0.5 g. per hour, the absolute percentage is altered by the amount of 1.21 per cent for the 0 to 5-micron fraction, and by the amount of only 0.73 per cent for the 5 to 10 and 10 to 20-micron fractions. The end-point rate can be ascertained well within the above rate variation of 100 per cent.

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[1] Stanton and Pannell, Nat. Physical Laboratory, Vol. 11, p. 293 (1914.)

EFFECT OF NOZZLE SIZE

For the 5 to 10-micron and coarser separations, it was found that the rate of fractionation and percentage in the fraction was independent of the nozzle size in the range 3 to 7 mm. internal diameter, corresponding to an air jet velocity of 10 to 50 meters per second. As standard, a velocity of 15 meters per second, or nozzle size of 5.5 mm., was adopted.

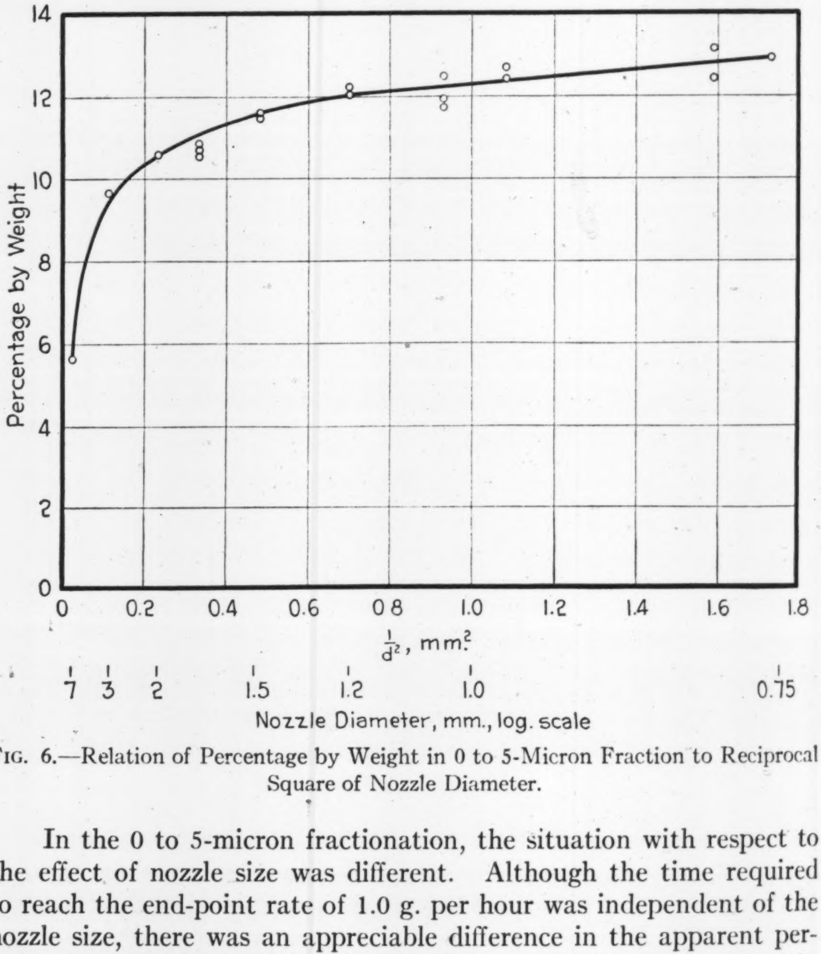

FIG. 6.—Relation of Percentage by Weight in 0 to 5-Micron Fraction to Reciprocal Square of Nozzle Diameter.

In the 0 to 5-micron fractionation, the situation with respect to the effect of nozzle size was different. Although the time required to reach the end-point rate of 1.0 g. per hour was independent of the nozzle size, there was an appreciable difference in the apparent percentage by weight in the fraction. This is shown in Table I and in Fig. 6 in which the percentage is plotted against the reciprocal square of the nozzle diameter, which is proportional to the velocity of the jet. It is seen that with decrease in nozzle size below 7 mm., the percentage in the 0 to 5-micron range increases at first rapidly and then relatively slowly.

In explanation of this result, it is believed that with a nozzle size substantially greater than 1.20 mm. there is not sufficient energy in the jet to "dissociate" the tightly clustered 0 to 5-micron grains.[1] With such coarser nozzles and especially with the 7-mm. nozzle, the residue, even with a rate of separation as small as 0.3 g. per hour, under the microscope was seen to contain a great many 0 to 5-micron particles. On the other hand, with the 1.20-mm. nozzle at the standard end-point rate of 1.0 g. per hour, the residue was virtually free of any such particles.

For nozzle sizes smaller than 1.20 mm., the slight increase in percentage in the 0 to 5-micron range appears on the basis of numerous experiments to be due to onset of breakdown or attrition[1] by the strong jet presumably of a softer grain present in the cement.

The critical and correct nozzle size for the 0 to 5-micron separation was empirically found to be that at which the air velocity at standard temperature and pressure is 81 meters per second, or 1.20-mm. inside diameter.

PROCEDURE IN MAKING AN ANALYSIS

In this work, the portland cements were analyzed into six particle-size fractions, 0 to 5, 5 to 10, 10 to 20, 20 to 40, 40 to 80, and 80 to (160) microns using a 25-g. sample and assuming a mean density of 3.0. For the 0 to 5-micron fraction the 9-in. settling tube was used with an air flow of 5.48 liters per minute, and inlet nozzle of 1.20 mm. inside diameter; separation of the 5 to 10-micron fraction was made with the same settling tube but with an air flow four times as great, or 21.92 liters per minute, and with a nozzle size of 5.5. mm. inside diameter. The same air flow and nozzle size were used for the 10 to 20, 20 to 40, and 40 to 80-micron fractions but with the 4.5, 2.25 and 1.12-in. settling tubes respectively. The required flow is calculated from the upward velocity of air required by Stokes' law to just separate a given particle size,[1] and from the diameter of the cylindrical portion of the settling tube.

As already pointed out, all fractionations are carried out to an end-point rate of 1.0 g. of material blown over per hour. In general, the fractionation will not be ended precisely at this point. Since the particle sizes that are blown over increase in size progressively and uniformly, the material that is blown over beyond the end-point rate of 1.0 g. per hour is to be credited to the next succeeding fraction; similarly if the separation is stopped short of an end-point rate of 1.0 g. per hour, the deficit is to be added to the fraction that is being separated.

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[1] P. S. Roller, U. S. Bureau of Mines *Technical Paper No. 490*, p. 1 (1931).

At the end of each separation, the total weight blown over and the weight of the residue are checked against the original weight. It has been found as the result of many observations that on the average there is a loss of 0.100 g. that can be attributed to adherence to the walls of the settling tube. A particle-size examination of the material thus adhering shows that it properly belongs to the next succeeding fraction. If the loss exceeds 0.100 g., the excess is attributed to loss by leakage and is credited to the given fraction.

TABLE II.—LOG OF FRACTIONATION.

Time, T_1	Time, T_2	ΔT, minutes	$\frac{1}{2}\Delta T$	T_R	$\Sigma\Delta T$	Weight, W_1	Weight, W_2	ΔW	W_R	$\Sigma\Delta W$
0 TO 5 MICRONS										
9:16.5	9:38.5	22	11	11	22	5.722	7.248	1.562	4.16	1.526
9:39.5	10:01.5	22	11	33	44	5.590	6.692	1.102	3.02	2.628
10:02.5	10:22	19.5	10	54	64	7.248	7.693	0.445	1.37	3.073
10:23	10:37.5	14.5	7	71	78	6.692	6.872	0.180	0.74	3.253
10:38.5	10:50	11.5	6	84	90	5.781	5.878	0.097	0.50	3.350
5 TO 10 MICRONS										
11:09.5	11:24.5	15	7.5	7.5	15	7.140	9.830	2.690	7.18	2.690
11:25	11:40	15	7.5	22.5	30	5.765	6.218	0.453	1.81	3.143
11:40.5	11:50.5	10	5	35	40	9.830	9.952	0.122	0.73	3.265
10 TO 20 MICRONS										
12:05.5	12:17.5	12	6	6	12	5.770	9.600	3.830	19.15	3.830
12:18.5	12:31	12.5	6	18	24	7.605	8.070	0.465	2.24	4.295
12:32	12:40	8	4	28	32	6.011	6.148	0.137	1.03	4.432

TABLE III.—CALCULATION OF PERCENTAGE BY WEIGHT IN FRACTIONS; ORIGINAL SAMPLE 25 G.

Fraction	Residue	Total Blown Over	Total Loss	Amount at End-Point Rate	Loss by Leakage, credited to fraction	Loss by Adherence to Tube, credited to next fraction	Excess Blown Over, credited to next fraction	Total in Fraction	Percentage in Fraction
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
0 to 5	21.541	3.350	0.109	3.020	0.009	0.100	0.330	3.029	12.12
5 to 10	18.137	3.265	0.139	3.143	0.039	0.100	0.122	3.612	14.45
10 to 20	13.635	4.432	0.070	4.381	.....	0.070	0.051	4.603	18.41

It is time saving and convenient to construct a "log of fractionation" as shown in Table II which gives results in the separation of the 0 to 5, 5 to 10, and 10 to 20-micron fractions. In this table W_R is equal to $\frac{60\Delta W}{\Delta T}$, and is the rate of fractionation in grams per hour at time T_R. The latter is equal to the sum of $\Sigma\Delta T$ of the preceding row and $\frac{1}{2}\Delta T$ of the same row.

When W_R of Table II is plotted on logarithmic paper against T_R, the curves shown in Fig. 7 are obtained. It is seen that below about 2 g. per hour, curves for all the fractions are straight lines of almost precisely the same slope. The intersection of these curves with the ordinate 1.0 gives the end-point time, T_R.

The amount of powder blown over up to the end-point rate is obtained by plotting from Table II on the same graph paper $\Sigma\Delta W$, or for greatest accuracy the decimal part of $\Sigma\Delta W$, against $\Sigma\Delta T$. The value of $\Sigma\Delta W$ at $\Sigma\Delta T = T_R$ is the desired quantity.

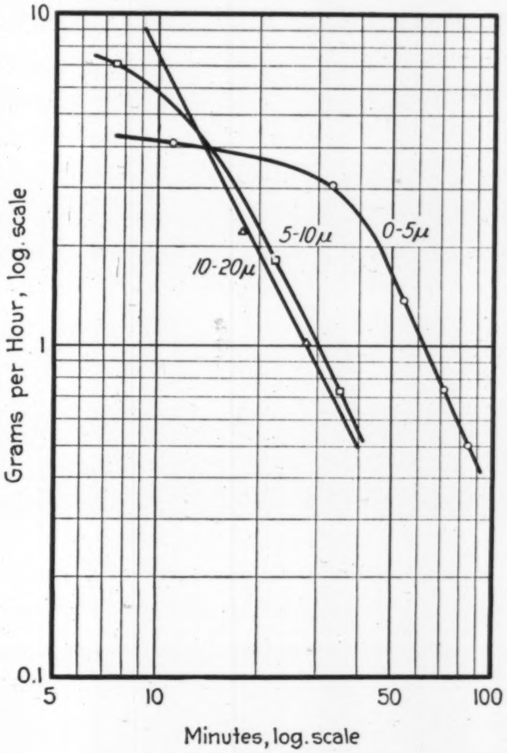

FIG. 7.—Relation of Rate of Separation to Time.

For determining the percentage by weight in each fraction it is convenient to construct a second tabulation as shown in Table III for the 0 to 5, 5 to 10, and 10 to 20-micron fractions of Table II.

At the end of a separation, gooseneck *G* and the lower conical portion of the settling chamber are tapped to shake down adhering particles.

The paper thimbles should be weighed under similar conditions of temperature and humidity.

The settling tubes are not cleaned except when a different type of powder is to be used. The tubes, which weigh but a few pounds, are shaken with a suitable liquid, rinsed with distilled water or other pure volatile liquid, and dried in a current of air.

TIME AND ACCURACY OF FRACTIONATION

The time of separation is affected by the rate of air flow and the strength of impact of the leafed spring steel tapper (*K* of Fig. 1), while the accuracy seems to depend upon the uniformity of fractionation which is affected also by the tapper, and upon the avoidance of loss of powder by adherence, leakage or mishandling.

In Table IV are given the time of fractionation, and the deviation of the percentage result averaged for each of the fractions of four brands of portland cement. It is seen that the maximum time required is 62 minutes for the 0 to 5-micron separation, and the minimum time 11 minutes for the 40 to 80-micron fraction. The average total time of separation into six discrete fractions is 169 minutes. It is to be noted that previously[1] with a lower air flow for the fractions above 5 microns and in the absence of continuous tapping of the settling tubes, the total time required was 18 hours as against less than 3 hours at present.

TABLE IV.—TIME AND ACCURACY OF FRACTIONATIONS.

FRACTION	AVERAGE TIME TO REACH END-POINT RATE, MINUTES	DEVIATION OF AVERAGE PERCENTAGE, PER CENT BY WEIGHT
0 to 5	62	±0.20
5 to 10	31	±0.22
10 to 20	29	±0.41
20 to 40	36	±0.30
40 to 80	11	±0.12
80 to (160)	..	±0.22

From the third column of Table IV it is seen that the results for the two finest fractions, 0 to 5 and 5 to 10-microns, are among the most accurate. The over-all average deviation of the percentage result is ±0.25 per cent. As more experience was gained in performing the analyses, the accuracy showed a tendency to increase so that the average deviation of the last cement analyzed was only ±0.17 per cent.

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[1] P. S. Roller, U. S. Bureau of Mines *Technical Paper No. 490*, p. 1 (1931).

METHOD OF MICROSCOPIC EXAMINATION OF FRACTIONS

To obtain a representative sample for examination under the microscope, the fractions were shaken with 95-per-cent alcohol, filtered over suction, and dried.

Previously the powder was dispersed dry on the slide with an electrically grounded platinum wire. To speed up the process of dispersion, a drop of liquid was later used. By far the most effective dispersing agent was found to be a 0.25-per-cent solution of saponin in 50-per-cent alcohol. If water alone is used, a germicide should be added to preserve the saponin.

A slight quantity of powder to be examined, which is less the smaller the particle size, is placed on the slide next to a drop of the saponin solution. With a thin platinum wire (No. 24 gage) fused into a glass tube, the liquid is added to the powder and the latter gently but thoroughly dispersed in all directions so as to give a thin cloudy layer. Evaporation is rapid, and the preparations are examined dry without a cover glass.

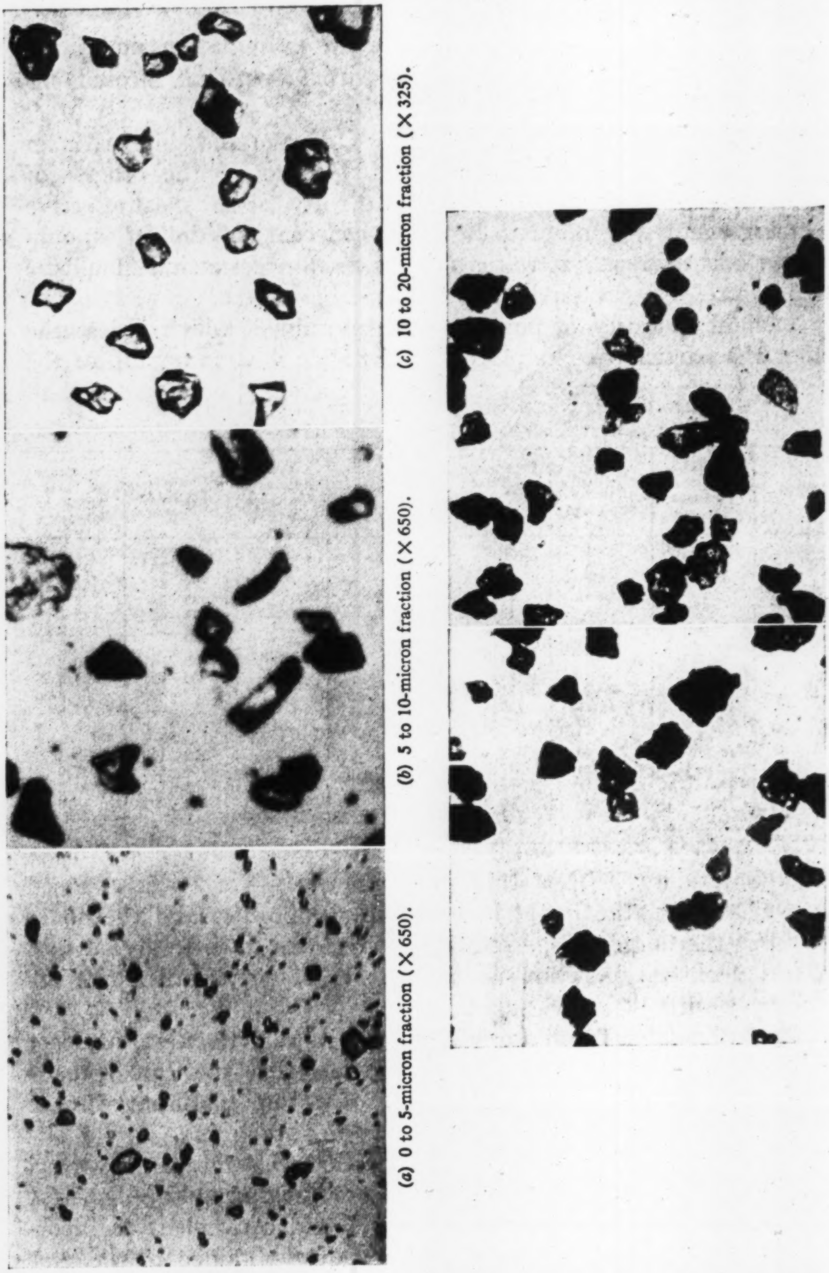
TABLE V.—PARTICLE SIZE DISTRIBUTION OF FRACTIONS.

Particle diameter taken as average of length and breadth.

Fraction	Total Number of Particles Counted	Particle Diameter Sub-range	Percentage of Total Surface in Sub-range	Fraction	Total Number of Particles Counted	Particle Diameter Sub-range	Percentage of Total Surface in Sub-range
0 to 5.......	1162......	0 - 1	60.0	20 to 40......	65........	16 - 20	1.3
		1 - 2	6.4			20 - 28	16.8
		2 - 3	3.6			28 - 36	36.7
		3 - 4	12.2			36 - 44	26.2
		4 - 5	13.4			44 - 52	13.7
		5 - 6	4.4			52 - 56	5.3
5 to 10......	65........	3 - 5	3.7	40 to 80......	62........	40 - 56	10.2
		5 - 7	24.1			56 - 72	24.8
		7 - 9	37.9			72 - 88	31.3
		9 - 11	26.4			88 - 96	33.8
		11 - 12	7.9				
10 to 20......	59........	6 - 10	2.2	80 to (160)...	63........	72 - 106	2.2
		10 - 14	17.3			106 - 138	37.0
		14 - 18	38.9			138 - 170	41.3
		18 - 22	34.5			170 - 202	19.5
		22 - 24	7.1				

The saponin solution probably owes its effectiveness, at least partly, to its surface tension; this is so low that the drop spreads quite readily over the slide. The use of a thin platinum wire of course obviates the danger of crushing the minute grains.

The length and breadth of each particle was measured with a calibrated 0.1 or 0.5-mm. ocular net. For measuring the depth of particles (larger than 5 microns) it was found convenient to incorporate a slight amount of extremely fine dust obtained in the first few minutes of separation of the 0 to 3-micron fraction of a carbon



(a) 0 to 5-micron fraction (× 650).

(b) 5 to 10-micron fraction (× 650).

(c) 10 to 20-micron fraction (× 325).

(d) 20 to 40-micron fraction (× 162).

(e) 40 to 80-micron fraction (× 81).

FIG. 8.—Photomicrographs of Particle Size Distribution.

black. The throw of the microscope in focusing on the surface of the grain and on a carbon-black dust particle gives the thickness of the grain.

Results of Microscopic Examination

In Table V is given the statistical count of the particle sizes (see Fig. 8) contained in each of the fractions separated, a particle diameter being defined as the average of the superficial length and breadth. The percentage of the total surface of each fraction included in the particle diameter sub-range given in the third column is equal to the ratio of the sum of the squares of the diameters in the sub-range to the sum of the squares of the diameters in the total range of the fraction.

It is seen that for each fraction there is undersize within a range of a few microns which for the 5 to 10 to 80 to (160)-micron fraction is respectively 3.7, 2.2, 1.3, 0.0, and 0.9 per cent, or an average of 1.6 per cent. There is also oversize within a range of several microns which for the 0 to 5 to 40 to 80 micron fraction is respectively 4.4 14.4, 7.1, 19.0, and 33.7 per cent, or an average of 17.7 per cent.

Table VI.—Surface Mean Diameter of Each of the Fractions.

Fraction (Based on Stokes' Law)	Mean Diameter by Stokes' Law	Particle Diameter Taken as Mean of Length and Breadth	Particle Diameter Corrected for Depth
0 to 5	2.5	2.06 ± 0.05	....
5 to 10	7.5	8.14 ± 0.25	7.65 ± 0.25
10 to 20	15.0	16.3 ± 0.9	14.1 ± 0.9
20 to 40	30.0	33.9 ± 1.7	29.2 ± 1.7
40 to 80	60.0	73.5 ± 0.5	63.2 ± 0.5
80 to (160)	(120)	143 ± 2	123 ± 2

Theoretical reasons have been previously given[1] for a certain amount of overlap of the Stokes' law boundaries of the fraction. In addition it has been pointed out above that due to the parabolic distribution of velocity in the settling tube there can be present oversize with a maximum diameter amounting to 1.41 times the theorectical maximum given by Stokes' law. In no case in Table V is the factor 1.41 exceeded, while generally it is only moderately approached.

The apparent oversize recorded in Table V has been accentuated in two ways. First, the arithmetic mean of the length and breadth has in every case been taken instead of the more correct harmonic mean.[1] While the difference between these means is generally negligible, for particles whose length varies greatly from the breadth the arithmetic mean gives too high a value. In the second place, the depth of the particles, which is usually considerably less than the mean of the length and breadth, has not been considered.

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[1] P. S. Roller, U. S. Bureau of Mines *Technical Paper No. 490*, p. 1 (1931).

The pronounced effect of the last factor, the depth of particle, on the apparent oversize is brought out clearly in Table VI which gives the surface mean diameter of each fraction, defined by the relation $\frac{\Sigma d^3}{\Sigma d^2}$, in comparison to the arithmetic mean of the theoretical Stokes' law limits. It is seen from column 3 that, excepting for the 0 to 5-micron fraction, the surface mean diameter calculated from the observed distribution of particle sizes taking a particle diameter simply as the mean of the superficial length and breadth, is well above the theoretical mean.

The depth of particle is substantially taken into consideration by applying to the surface mean diameter just calculated a correction for the average "clevage ratio" $a:b:c$.[1] This was found to be 1:0.72:0.72 for the 5 to 10-micron fraction, and closely to approximate 1:0.67:0.47 for both the 10 to 20 and 20 to 40-micron fractions. When correction for the average depth of particle is applied, the surface mean diameter, from the fourth column of Table VI, is now seen to be equal, within error of measurement, to the theoretical mean diameter derived from Stokes' law.

It is to be noted that, to a greater extent than observed previously,[1] the mean diameter of the 0 to 5-micron fraction in Table VI is below the theoretical mean. Furthermore, in Table V the distribution of particle sizes in the 0 to 5-micron fraction is not normal, as for practically all the other fractions, a normal distribution possessing a maximum percentage near the middle of the fraction.

The observed large displacement of particle sizes toward the 1-micron range which gives rise to the differences noted between the 0 to 5-micron and the other fractions is believed not to be real, but is attributed to attrition. Since no constant end rate of fractionation[1] was observed, the attrition pertains only to the more easily disrupted particles below 5 microns, and consequently does not affect the percentage by weight in the 0 to 5-micron range.

It is concluded, especially in view of the moderate quantity of material in the 0 to 5-micron fraction, that for it, as well as for the other fractions, the true surface mean diameter is the mean of the theoretical Stokes' law limits.

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[1] P. S. Roller, U. S. Bureau of Mines *Technical Paper No. 490*, p. 1 (1931).

RESULTS OF ANALYSIS OF PORTLAND CEMENT POWDERS

The percentage by weight in each of the fractions beginning 0 to 5-microns is shown in Table VII for four brands of portland cement. In the last two rows of this table are given the surface mean diameter of the powder as a whole and the dispersion. These quantities are calculated from the percentage by weight of each of the fractions[1], taking the mean diameter of each fraction as the mean of the Stokes' law limits. The surface mean diameter varies from 10.4 to 10.9, while the dispersion varies from 13.2 to 15.7.

Particle-size analyses beginning 0 to 10 microns rather than 0 to 5 microns have been recorded in a few places in the literature. Gonell[2] working with an air analyzer apparatus similar in construction to that of Pearson and Sligh[3] obtained for three cements 29.0, 31.7, and 32.5 per cent by weight in the 0 to 10-micron range. These results are well above any of the percentages recorded in Table VII. With the Gonell apparatus, Kühl[4] obtained for one cement a value about 13 per cent less, or 18.2 per cent.

TABLE VII.—PARTICLE SIZE DISTRIBUTION, SURFACE MEAN DIAMETER, AND DISPERSION OF FOUR BRANDS OF PORTLAND CEMENT.

	PARTICLE SIZE DISTRIBUTION, PER CENT BY WEIGHT			
FRACTION, MICRONS	BRAND I	BRAND II	BRAND III	BRAND IV
0 to 5	12.06	12.64	12.15	11.58
5 to 10	14.47	13.78	14.21	16.05
10 to 20	16.67	17.55	18.71	21.84
20 to 40	23.73	25.44	27.89	30.84
40 to 80	27.26	25.23	24.06	17.55
80 to (160)	5.81	5.36	2.98	2.14
Surface mean diameter, d_s	10.9	10.7	10.7	10.4
Dispersion, σ_s	15.7	15.5	14.6	13.2

With a self-recording Wiegner sedimentation apparatus, Kühl and Tokune[5] obtained for the 0 to 10-micron fraction of four cements, a trace, 14.4, 14.6, and 21.6 per cent—decidedly low results. By direct weighing of the sediment, Taylor[6] obtained for the 0 to 10-micron range the plausible value of 28 per cent.

It is illuminating to plot from Table VII in the manner previously described,[1] $\phi\,(d) = \dfrac{W}{\Delta\, d}$ against log d_s, where W is the weight per cent of a fraction, Δd is the difference between the Stokes' law upper and lower particle-size limits, and d_s is for each fraction the mean of the limits. In such a plot, the area under the curve represents the surface area between any two particle sizes.

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[1] P. S. Roller, U. S. Bureau of Mines *Technical Paper No. 490*, p. 1 (1931).

[2] Gonell, *Zement*, Vol. 17, p. 256 (1928).

[3] Pearson and Sligh, U. S. Bureau of Standards *Technologic Paper No. 48* (1915).

[4] Kühl, *Zement*, Vol. 19, p. 604 (1930).

[5] Kühl and Tokune, *Zement*, Vol. 17, p. 256 (1928).

[6] Taylor, *Rock Products*, Vol. 35, No. 7, p. 46 (1932).

The curves obtained for all the cements are similar in form to that illustrated in Fig. 9 for cement brand III. For the 0 to 5-micron fraction, the distribution is assumed to be normal, as it is for the other fractions, so that the left branch of the curve below the mean diameter of 2.5 microns may be taken as practically a straight line approaching the abscissa axis at 0.8 micron such that the area beneath the line is somewhat less than the area between 2.5 and 5 microns with ordinate equal to that at 2.5 microns.

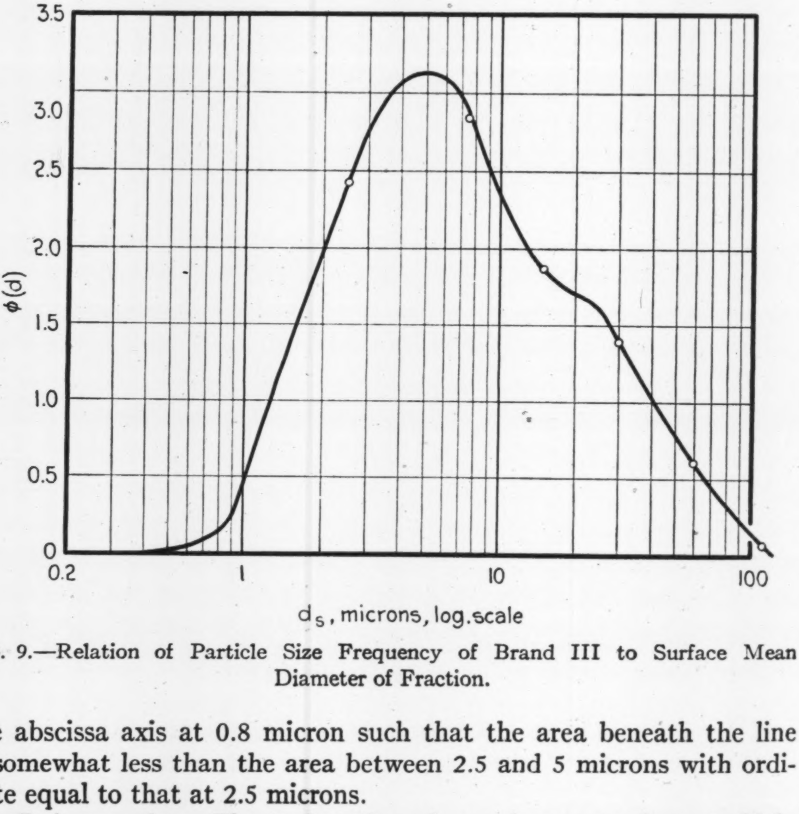

FIG. 9.—Relation of Particle Size Frequency of Brand III to Surface Mean Diameter of Fraction.

It is seen from Fig. 9 that there is a primary maximum which, averaged over all the cements, is at 5.4 microns; there is also a second hidden maximum at an average particle size of 22 microns. The second maximum indicates that there is a second major constituent in the cement of different crushing strength or hardness. This result is of interest for cement technology because it shows that there is a definite segregation during grinding of the constituents of portland cement into particle-size categories.

Gonell[1] and Kühl[2] have found a relatively high ignition loss for the finest particle-size fractions. From a chemical analysis by Gonell[1] it appears that there is a concentration of alumina, and possibly also of tricalcium silicate, in the 0 to 10 as against the 10 to 20-micron fraction.

It is often stated that clinkers ground in the laboratory cannot be made to simulate the particle-size distribution and fineness of clinkers ground in a mill. In Table VIII are given the results of analysis of three clinkers that were ground in 50-lb. batches in a laboratory disk grinder and pebble mill. It is seen that the distribution of particle sizes among the different fractions as well as the surface mean diameter is reasonably the same as that for the commercial portland cements. Also when ϕ (d) is plotted against log d_s, the form of the curves as regards the primary and secondary maxima is similar. However, the location of the maxima is displaced for the laboratory ground clinker to a coarser size of particle, from an average of 5.4 to 6.1 microns for the primary maximum, and from 22 to 43 microns for the secondary maximum.

TABLE VIII.—PARTICLE SIZE DISTRIBUTION, SURFACE MEAN DIAMETER, AND DISPERSION OF THREE LABORATORY GROUND CLINKERS.

FRACTION, MICRONS	PARTICLE SIZE DISTRIBUTION, PER CENT BY WEIGHT		
	BRAND I	BRAND II	BRAND III
0 to 5	13.00	13.90	13.39
5 to 10	14.00	14.42	17.95
10 to 20	17.13	17.17	20.50
20 to 40	22.65	23.90	29.80
40 to 80	29.15	27.57	18.17
80 to (160)	4.08	3.04	0.19
Surface mean diameter, d_s	10.6	10.2	9.6
Dispersion, σ_s	15.4	14.7	12.1

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[1] Gonell, *Zement*, Vol. 17, p. 256 (1928).

[2] Kühl, *Zement*, Vol. 19, p. 604 (1930).

DISCUSSION

Mr. J. C. Pearson.[1]—In view of the interest now being taken by cement manufacturers in the particle size distribution of their product, this paper is a timely one and will undoubtedly receive considerable attention. There is much in it that will bear critical thought and study. My immediate reaction is that certain questionable assumptions may have been made, or there may exist the possibility of certain errors, which mathematical treatment tends rather to camouflage than to disclose. At any rate, certain questions arose in my mind which no one could probably answer unless he were quite familiar with the apparatus and had used it extensively.

I am wondering whether the very high velocity of the jet is not causing considerable attrition; whether there are electrical effects which are not entirely taken care of? I am wondering whether the velocity gradient across the large stack is not somewhat different from that which might be calculated by the law of flow? It has been our experience that, in a stack which has a comparatively low ratio of length to diameter, we cannot assume that the velocity has straightened out and reached a constant gradient within the length of the stack; in other words, the high axial velocity above the inlet, and possibly the general turbulence in the lower part of the stack, seem to persist in perceptible degree at the top of the stack, and therefore cause a removal of larger particles than would be the case if the normal gradient obtained.

Mr. L. T. Work.[2]—This paper is an interesting contribution to the literature on air separation, and by its application to portland cement it suggests potential practical benefits which may accrue through rapid measurement of cement fineness.

Using a Stokes' law diameter as the measurement of particle size, Mr. Roller finds very little overlap between separations. In contrast to this, Geoffrey Martin[3] carefully separated sand with an air separator into a narrow size range and then measured its dimensions microscopically, using the statistical diameter. He found that successive separations after a certain point did not make a more uniform material. An examination of his data will show that after many separations there is a greater spread in particle size than that found by Roller. In Martin's case it is probable that the statistical diameter is largely responsible for the lack of uniformity of size. The very method itself can show an appreciable spread with a group of identical particles each oriented differently with respect to the microscopic scale.

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[1] Director of Research, Lehigh Portland Cement Co., Allentown, Pa.

[2] Assistant Professor of Chemical Engineering, Columbia University, New York City.

[3] Geoffrey Martin, *Transactions*, Inst. Chemical Eng. (British), Vol. 4, p. 42 (1926).

Reference has been made to the classic paper by Pearson and Sligh and the comment made that they showed higher percentages of fine cement than those found in Roller's work. Cement manufacturers are not grinding their product less finely at this date than in former years. It is more likely that the particular diameter used in Pearson and Sligh's paper is sufficiently different from the diameter used in Roller's paper to account for this difference. I therefore raise these questions: (1) How does the Stokes' law diameter compare with the diameters used in other methods of fineness measurement? (2) Can it be shown that the Stokes' law diameter is so much more closely a measure of separation characteristics that it reveals but little overlap?

Roller presents a distribution curve for portland cement in which two peaks are observed, and this, combined with chemical analysis from the literature, is a basis for the deduction about the grindability of different ingredients within the cement. If this were true, a homogeneous material would not show two peaks. Actually the type of curve form noted by Roller is typical of the grinding of essentially homogeneous material. The curve fits a grinding relation which I have developed largely through experiments with silica. A paper on this subject was recently presented before the American Society of Mechanical Engineers.[1]

While I will grant that there is a difference in grindability between dicalcium and tricalcium silicate, the inference in Roller's paper does not appear to be substantiated by sufficient proof. High ignition loss and variation in chemical analysis are likely to be affected by gypsum and such other mineral matter as enters with it. Positive identification of the silicates and their relation to his curve would be more effective.

MR. P. S. ROLLER[2] (*author's closure*).—The existence of the effects or of possible effects described by Mr. Pearson have been taken into consideration in the course of this work. The questions of possible attrition, electrical effects, parabolic flow, and persistence of jet velocity, have been discussed in detail in the present paper or in

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[1] L. T. Work, "An Analysis of Crushing and Pulverizing Processes," presented at the National Process Meeting, Buffalo, N. Y., June 6 to 8, 1932, of the American Society of Mechanical Engineers.

[2] Associate Chemist, U. S. Bureau of Mines, Nonmetallic Minerals Experiment Station, New Brunswick, N. J.

U. S. Bureau of Mines *Technical Paper 490*, and in reply reference may be made to this discussion.

The air analyzer used by Pearson and Sligh, and Martin and co-workers, referred to by Mr. Work, differs in certain essential features from the apparatus described in the present paper, but chiefly in the fact that in one case the powder sample is stationary, whereas in the other case the powder sample is in dynamic motion with respect to the air inlet. I would ascribe differences of performance noted by Mr. Work not to the manner of defining particle diameter, but rather to differences in construction and operation of apparatus. For example, separations by Pearson and by Martin begin with 0 to 20 microns, whereas with the present apparatus separations begin with 0 to 5 microns. As a second difference, Martin *et al.*[1] found that the distribution of the particle size and mean diameter of the fraction obtained in the first fifteen minutes and in the last fifteen minutes (after 2 hours blow) was nearly the same, which is in striking contrast to the results obtained with the apparatus described in the present paper.

The particle diameter defined in the present work as the mean of the linear dimensions, is a direct measure of the specific surface of a particle and thus has a desired physical significance. Particle diameter measured in any other one of a number of possible ways no doubt would show some differences in magnitude. Considering especially the fact that the "cleavage ratio" for portland cement averages well above 0.5, such differences would generally be small when measurement is made of a large number of particles as compared to that due to differences in apparatus.

The present paper is by no means intended to be a discussion of grinding processes. The two humps obtained in the size-frequency distribution curve as defined pointed, in accordance with the usual interpretation of such frequency curves, to the presence of two major constituents of different grindability in the clinker. The result obtained was too definite and seemed too interesting to allow it to pass unnoticed. Of course, there is no evidence in the present work to prove or disprove Mr. Work's contention that two humps in the frequency curve should be shown by an essentially homogeneous material. Publication by Mr. Work or by other investigators of experimental results in this direction can be looked forward to with interest.

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[1] *Transactions*, Ceramic Soc., Vol. 23, p. 79 (1924).

TESTS ON CONSISTENCY AND STRENGTH OF CONCRETE HAVING CONSTANT WATER CONTENT

By Inge Lyse[1]

Synopsis

In this paper test data are presented which show that the consistency of the concrete remains nearly constant regardless of the richness of mix, if the type and gradation of the aggregates and the water content per unit of fresh concrete remain constant. One series of tests included five different brands of cement and showed that the brand of cement had a slight effect upon the consistency of the concrete, while the richness of the mix for each cement had practically no effect. Another series of tests included nine different concrete aggregates and showed that the type and gradation of aggregates had a great effect upon the water requirement for a given consistency of the concrete, while for a given type and grading of aggregates and a constant water content the consistency was nearly the same for all mixes. Since the cement and aggregate contents were the only variables in these concrete mixes, the strength of the concrete was necessarily determined primarily by the cement content. It is shown that the relation between the cement-water ratio and the strength of the concrete was a straight line, and therefore the relation between the strength and the cement content was also a straight line for mixes of constant water content. Thus the following conclusions are drawn: The cement is the strength-giving element in concrete. Above a given minimum number of cement particles necessary to give workability and binding strength to the concrete, the strength increases in direct proportion to the increase in number of cement particles in a unit of water. For ordinary aggregates, a change in the richness of a concrete mix of a given consistency is accomplished by keeping the water content constant and substituting 0.85 lb. of aggregate for each pound decrease in the cement content, or *vice versa*.

Introduction

The consistency of concrete as measured by the slump cone has been found to remain practically constant, regardless of the richness of the mix, if the water content per unit of concrete and the type and gradation of the aggregates remain the same. In order to investigate this important property of concrete two series of tests were carried out at the Fritz Engineering Laboratory of Lehigh University during the winter of 1931–1932. In one of these series of tests the type and gradation of aggregates were the same throughout the series and the water content per cubic yard of concrete was kept constant also. Thus the only variables were the cement content and its complement, the corresponding aggregate content. Five different brands of cement were included in the tests, and four mixes of different richness were used with each brand of cement.

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In the second series of tests aggregates from nine different sources were included and the water content was kept the same for all mixes containing a given aggregate. The gradation of each aggregate and the brand of cement used were the same for all mixes. Three mixes of different richness were used with each aggregate.

OUTLINE OF TESTS

The aggregates used in the first series of tests were the same as those which have been used in ordinary concrete investigations at the Fritz Engineering Laboratory during the preceding two years. The aggregates were siliceous sand and gravel from the Warner Co. plant at Morrisville, Pa. The sand had a fineness modulus of about 2.80 and was well suited for concrete. The gravel was graded so as to contain 40 per cent by weight, between No. 4 and $\frac{3}{8}$-in. sieves and 60 per cent between $\frac{3}{8}$- and $\frac{3}{4}$-in. sieves. The sand-coarse aggregate ratio was 1:2 by volume of dry rodded materials. The mixes by weight of the dry materials were: 1:1.64:3.26, 1:2.19:4.35, 1:2.74:5.43 and 1:3.29:6.51. The net water content was 36 gal. or 300 lb. per cu. yd. of freshly placed concrete for all the mixes, regardless of the brand of cement.

The concrete was mixed in a $2\frac{1}{2}$ cu. ft. capacity power mixer and a slump test was taken on each batch immediately after mixing. Standard 6 by 12-in. concrete cylinders were made and tested at the ages of 7 days and 3 months. The 7-day specimens were cured in the moist room for 3 days and then in the air of the laboratory for the remaining 4 days. The 3-month specimens were cured in the moist room until the day of test.

The mixes in the second series of tests were so designed as to have cement-water ratios of 1.25, 1.61 and 2.25 by weight, which correspond to water contents of 9, 7 and 5 gal. per sack of cement, respectively. The aggregates included river sand and gravel, and also crushed limestone as fine and coarse aggregates. The sand-coarse aggregate ratio was $1:1\frac{1}{2}$ by weight for all mixes, and the gradation of each aggregate was as received from the dealer.

In designing the mixes, a trial batch was made for each type of aggregate in order to determine the water requirement for a given slump. In making a trial batch a 1:2:3 mix by weight was used.

The water was added in known amounts until the desired slump of the mix was reached. A computation of the volume of the concrete in the trial batch gave the amount of water per unit of concrete. The net water content per unit of concrete was kept constant for all the mixes which had the same aggregate as that used in the trial batch. The cement content was determined by multiplying the net water content by the given cement-water ratio, and the change in richness of the mixes was accomplished by substituting 0.85 lb. of aggregate, of the type and gradation used, for each pound decrease in cement content, or *vice versa*. An amount of water corresponding to one per cent of the weight of the dry aggregate was added to all mixes in both series of tests to allow for absorption. The consistency of these mixes was measured by means of the slump test.

TABLE I.—SLUMP OF CONCRETE MIXES CONTAINING FIVE DIFFERENT BRANDS OF CEMENT.

Mix by Volume of Dry Rodded Materials	Mix by Weight of Dry Materials	Slump, in.					
		Cement A	Cement B	Cement C	Cement D	Cement E	Average
1:1½:3	1:1.64:3.26	2½	1½	3	2½	5½	3
1:2:4	1:2.19:4.35	2¼	1½	5¾[a]	2½	4½	3¼
1:2½:5	1:2.74:5.43	3¾	1½	5	2	4½	3½
1:3:6	1:3.29:6.51	3	1½	2½	3	5	3
Average		3	1½	4	2½	5	3¼

[a] Fell down.

TEST DATA

The slumps of the concrete mixes used in the first series of tests are given in Table I. The average strength of three cylinders of a kind is plotted in Fig. 1 for 7-day tests and in Fig. 2 for 3-month tests. The slumps observed in the second series of tests are given in Table II.

CONSISTENCY OF CONCRETE HAVING CONSTANT WATER CONTENT

In Table I the slumps have been tabulated for all the mixes included in the first series of tests. It is noted that for cement A the slump varied from a minimum of 2¼ to a maximum of 3¾ in. for the four different mixes. The other cements showed similar relations. Cement B had 1½ in. slump for all mixes, cement C varied from 2½ to 5¾ in., cement D from 2 to 3 in. and cement E varied from 4½ to 5½ in. The last column of Table I gives the average slump for the same mix regardless of the brand of cement used. These average slumps are very nearly the same for the four mixes, being 3, 3¼, 3½ and 3 in. It is noted from this table that the variation between the slumps for concrete containing different brands of cement was considerably greater than the variation between slumps of concrete mixes containing the same cement. For the aggregates used in this series of tests the slump remained nearly constant for all mixes which had the same brand of cement and which had a constant water content of 36 gal. or 300 lb. per cu. yd. of concrete. It is also noted that the brand of cement had a consistent effect upon the slump of the concrete. This effect was so small, however, that it is reasonable to conclude that in most cases a mix which is placeable when one brand of cement is used will also be placeable when another brand is used.

TABLE II.—SLUMP OF CONCRETE MIXES CONTAINING NINE DIFFERENT AGGREGATES.

	Type of Aggregate		Net Water Content, gal. per cu. yd.	Slump, in.			
	Fine	Coarse		Mix Having Cement-Water Ratio of 2.25	Mix Having Cement-Water Ratio of 1.61	Mix Having Cement-Water Ratio of 1.25	Average
No. 1	Limestone screenings	Crushed limestone	45.3	2	2¾[a]	2¾[a]	2½
No. 2	Sand	Gravel	37.0	2	3[b]	3[b]	2¾
No. 3	Sand	Pea gravel	44.1	3½	3½	4	3¾
No. 4	Sand	Gravel	38.0	1¾	1	1½	1½
No. 5	Sand	Gravel	45.3	5	5	6	5¼
No. 6	Limestone screenings	Crushed limestone	43.0	½	1	1	¾
No. 7	Sand	Gravel	40.5	½	2¼[c]	2¼[c]	1¾
No. 8	Sand	Pea gravel	41.5	4¾	5	3½	4½
No. 9	Sand	Gravel partly crushed	41.5	3½	5	3	3¾
Average				2.6	3.2	3.0	2.9

[a] 0.7 gal. per cu. yd. added to mix.
[b] 0.5 gal. per cu. yd. added to mix.
[c] 1.0 gal. per cu. yd. added to mix.

In Table II the slumps are given for the three concrete mixes in which nine different aggregates were used. It is noted that the water requirement for a given slump is quite different for concretes containing different aggregates. While concrete containing aggregate No. 2 required only 37 gal. of water per cubic yard to produce a 2- to 3-in. slump, concrete containing aggregate No. 1 required 45.3 gal. per cu. yd. for the same slump. In other words, for concretes having paste of the same cement-water ratio, the amount of paste required to produce a 2- to 3-in. slump was more than 20 per cent

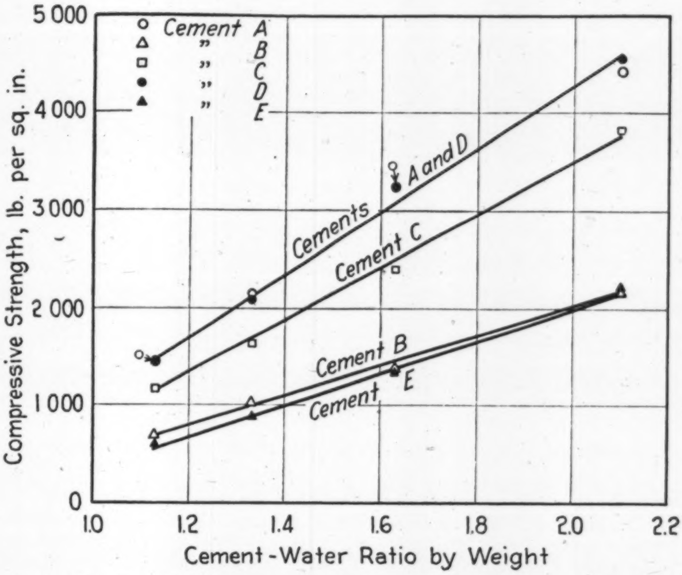

FIG. 1.—Relation Between Strength and Cement-Water Ratio at the Age of 7 Days.

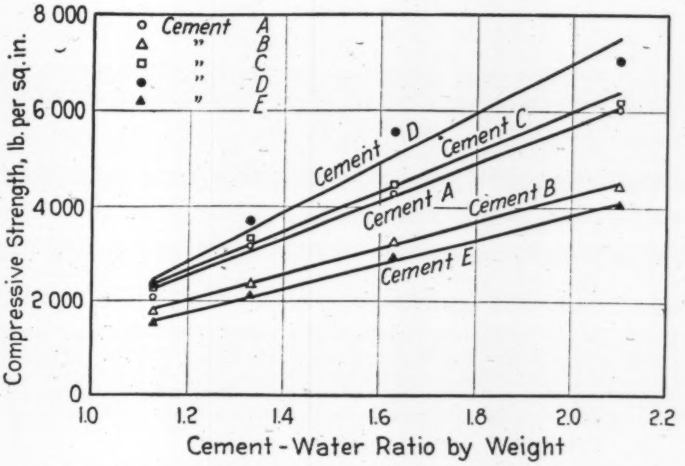

FIG. 2.—Relation Between Strength and Cement-Water Ratio at the Age of 3 Months.

greater for the concrete containing aggregate No. 1 than for concrete containing aggregate No. 2. Thus the economy of the mix was dependent to a large extent upon the type and gradation of the aggregates.

The slumps for the three mixes having the same type of aggregates and a constant water content were nearly equal for all the aggregates included in this series. In order to increase the workability, the water content was slightly increased for the two leaner mixes for three of the nine aggregates used. This additional water consequently increased the slump of the mix. The high degree of uniformity in slump for the different mixes, regardless of aggregates used, is illustrated by the average values given in Table II. The average slumps for the mixes having cement-water ratios of 2.25, 1.61, and 1.25 were 2.6, 3.2 and 3.0 in., respectively. If the water content had not been increased in any of the mixes the agreement would have been still better.

This series of tests including nine different aggregates showed that the consistency of the concrete, as measured by the slump, remained nearly constant regardless of the richness of the mix as long as the type and gradation of aggregates and the water content per cubic yard of concrete remained constant.

This uniformity in the workability for concretes having a given type and gradation of aggregates is very useful in designing concrete mixes. Since the water content remains constant, the amount of solids per unit of concrete is also constant. Thus a change in the cement content requires a corresponding change in the aggregate content if the consistency is to remain the same.

STRENGTH OF CONCRETES OF CONSTANT WATER CONTENT

The strengths of the concretes at the ages of 7 days and 3 months are shown in Figs. 1 and 2 for the first series of tests. In these figures the strength of the concrete is plotted against the cement-water ratio by weight. It is noted that the strength-cement-water relation for both ages of test is very nearly a straight line for any given brand of cement used. Since some of the brands of cement used were of the high-early-strength type and others were ordinary portland cements, the strengths for the five different brands differed very much. This large range in strengths is well illustrated in Figs. 1 and 2.

Figures 1 and 2 show that the relation between strength and cement-water ratio of a concrete mix is nearly a straight line within a range of mixes varying from 1:1½:3 to 1:3:6, for any given brand of cement. Since the water content per cubic yard of concrete remained the same for all the mixes the cement-water ratio is directly proportional to the cement content per cubic yard of concrete. Thus the strength of the concrete was found to be proportional to the variation in cement content. This leads to the conclusion that the cement is the strength-giving constituent in concrete and that above a minimum number of cement particles necessary to give workability and binding strength to the concrete, the strength of the concrete increases in direct proportion to the increase in number of cement particles in a unit of water. In other words, the strength of the concrete is determined by the concentration of cement particles in the paste.

SIGNIFICANCE OF RESULTS

Since for concrete having a given consistency and a given type and gradation of aggregates, the water content per cubic yard is nearly constant, the amounts of solid matter in a cubic yard of concrete is also constant. Thus to increase the richness of the mix and to keep the consistency constant, the absolute volume of the increase in the cement content must be equal to the absolute volume of the decrease in the aggregate content, and to decrease the richness, *vice versa*.

A change of one pound in the cement content necessitates a change of $\frac{ga}{gc}$ pounds in the aggregate content, where ga and gc are the specific gravities of the aggregate and cement respectively. Common aggregates and cements have specific gravities of 2.65 and 3.10, respectively, so that the relation $\frac{ga}{gc} = \frac{2.65}{3.10} = 0.85$. This leads to the simple conclusion that a change in the richness of the concrete mix is accomplished by substituting 0.85 lb. of aggregate for each pound decrease in cement content or *vice versa*, for concretes of a constant consistency.

By means of the straight-line relation between the cement-water ratio and the strength of concrete, the magnitude of the change in the cement content for a given change in the strength of the concrete is readily determined. Since the strength of the concrete is given by the formula: $S = A + B\frac{c}{w}$ where A and B are constants depending upon the materials used and the conditions of test, and c and w are amounts of cement and water, respectively, the equation for concrete mixes having a constant water content becomes: $S = A + \frac{B}{w}c = A + Kc$. Thus the cement content necessary to produce a given strength is given by $c = \frac{S-A}{K}$. Fortunately the straight-line relationship is applicable for all practical mixes for a given brand of cement so that the change in cement content required for a given change in strength is determined directly from the amount of cement necessary to give the required cement-water ratio.

SUMMARY

1. Concrete mixes having a given type and gradation of aggregates, a given brand of cement and a constant water content per cubic yard of concrete were found to have nearly the same consistency, regardless of richness of mix.

2. The brand of cement used had a slight effect upon the consistency of the concrete.

3. The water requirements for concrete of a given consistency varied considerably with the type and gradation of fine and coarse aggregates.

4. For all the aggregates used the consistency remained practically the same so long as the water content and the type and gradation of the aggregate remained the same.

5. The strength of the concrete mixes increased proportionately with the increase in the cement-water ratio for any brand of cement used and for both ages at test.

6. The conclusion is reached that the cement is the strength-giving constituent in concrete and that above a minimum number of cement particles necessary to give workability and binding strength to the concrete, the strength of the concrete increases in direct proportion to the increase in number of cement particles in a unit of water.

7. Each brand of cement had its own straight-line relation between the strength and the cement-water ratio of the concrete.

8. In designing concrete mixes of equal consistency, the water content per cubic yard of concrete and the type and gradation of aggregates should be maintained the same and the change in richness of the mix should be accomplished by substituting $\left(\frac{\text{specific gravity of aggregates}}{\text{specific gravity of cement}} = \text{approximately } 0.85\right)$ lb. of aggregates for each pound decrease in cement content, or *vice versa*.

DISCUSSION

MR. M. O. WITHEY[1] (*presented in written form*).—In this paper, Mr. Lyse has apparently brought forth a considerable simplification of the method of procedure in designing concrete mixes. The fundamental basis for his method is that the compressive strength of concrete increases lineally with the cement-water ratio by weight. It does not appear to the writer that this relationship always holds. In Fig. 1 of Mr. Lyse's paper, it will be observed that the curve for cement A is not strictly a straight line and that in Fig. 2 the curve for cement D is not a straight line. In Fig. 2 these discrepancies will be more apparent if the strength scale is made the same as in Fig. 1. I believe that similar results will be shown if the data for series 210 of the report of the Director of Research of the Portland Cement Association are plotted. I also have plotted a similar relationship for a series of tests which were made in our laboratory with Janesville sand and Janesville gravel which does not give a linear relationship, particularly for the higher cement-water ratios. These discrepancies lead me to believe that this method affords a good approximation for designing mixes when the basic data are obtained from cement-water ratios which do not differ widely from the ratios to be used in a specific design, but I am uncertain regarding the accuracy of the method when the basic water ratios do differ materially from those used in the design.

MR. A. D. CONROW[2] (*presented in written form*).—The test data of the paper seem to show that the consistency of concrete remains nearly constant regardless of the richness of the mix, if the type and gradation of the aggregates and the water per unit of fresh concrete remain constant. This condition is correct for a certain range of mixtures, since the term nearly constant is used. The variation in consistency under the above stated conditions is so small over the range of variation in cement content that is commonly found in concrete, that it may be considered practically constant. The condition, however, is contrary to the well-known fact that the finer the gradation of a mixture of dry materials, the greater the quantity of water required for a given consistency. The richness of the mix may be increased without changing the volume of concrete by adding, say one pound of cement, and removing 0.85 lb. of aggregate when the specific gravities of the materials are those common in concrete materials. This results in the addition of one pound of very fine material and the removal of 0.85 lb. of relatively coarse material. The gradation of the new mixture will be finer. More water will be required to bring to the given consistency unless some compensating factor is present. The compensating factor over the range of common mixtures is the greater separation of the aggregate particles by cement paste as a lubricant giving greater mobility to the aggregate particles. The principle set forth here can apply only over a very limited range of richness of mix.

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[2] Research Engineer, Ash Grove Lime and Portland Cement Co., Chanute, Kans.

The maximum size of aggregate is not given for Table I, but it is believed to be 1 in. or larger. It is believed that the smaller the size of aggregate, the less is the likelihood that the consistency will remain constant under the conditions given.

The fact that the consistency obtained with different brands of cement in the same mix is not the same has occupied the attention of cement manufacturers for some time, and has resulted in the raising of the question as to whether the strength of concretes of the same water-cement ratio and mix are fair comparisons of the concrete-making qualities of the cements to be compared. A fair comparison of the concrete-making quality of a number of cements should be on the basis of concrete having the same consistency and the same cement content per unit of volume of concrete.

The straight-line relation of strength to cement-water ratio by weight is believed to be a better method of showing the strength and water quantity relations than the familiar curve developed by Abrams of water-cement ratio by volume. The form and equation of the curve is easier to handle.

The cement-water ratio curves of Figs. 1 and 2 of the paper do not show the true relative strengths of the different cements in a given concrete. Cement B shows rather low strength compared to the other cements but observation of Table I shows that more water is necessary to bring concrete made with this cement to the same consistency as was obtained with the others. This would mean that if compared with the same concrete, the cement-water ratio would be lower for the same consistency, and its relative strength would be still lower than is shown by the curves.

The fact that changes in gradation of a concrete mixture causes a change in the water quantity required to bring a mixture to a given consistency, is one which has been taken into account in the methods of design of concrete mixtures for some time, and it is this principle which conflicts with the conditions given at the beginning of the paper, for a change in richness of the mix will cause a change in gradation of the mixture if the gradation of the aggregate remains the same. In the opinion of the writer, this variation in gradation may best be dealt with by use of a fineness modulus similar to that developed by Abrams. Greater accuracy could probably be attained by closer sizing of the sieves but would be somewhat impractical. The water requirements of a mix may be quite closely obtained if the gradation of the mix is known and certain factors obtained which are involved in the nature of the cement used, and the nature of the aggregate particles.

MR. F. R. MCMILLAN.[1]—I think Mr. Lyse has made a distinctly valuable contribution. I do not believe he will disagree with Mr. Withey's comment which will probably be agreed to by anyone who is a careful student of the subject. Unfortunately, we have learned in the field of concrete to worship curves and formulas too much and failed to keep in our minds some of the limitations of our material and the basic data. Any method as simple as that developed by Mr. Lyse and which at the same time predicts the strength as accurately, should be of permanent value to the profession. The very fact that the points from Mr. Lyse's tests do not line up perfectly is evidence that we must not rely too implicitly on formulas or curves. We should, however, recognize any device that will simplify or speed up our calculations and should take full advantage of it within the limits of its application.

I like very much the simplicity of Mr. Lyse's method and hope to see it quite generally adopted. By it we can establish for any given group of materials a basic relationship for the design of mixtures that is simple and probably involves less error fundamentally than is normally found in the measurement of materials. Our own data show slight variations from Mr. Lyse's data in respect to the constancy in water content for different mixes of the same consistency. For example, on the basis of constant remolding effort (in the remolding test) we find an increase in water content as the mix becomes leaner. On the other hand, our data indicate that the approximate relationship between total water content and consistency holds over a wider range in proportion of sand to coarse aggregate than would appear from Mr. Lyse's discussion.

All that should be expected of any method of design is to give quickly an approximation to a desirable mix which can finally be adjusted at the mixer to give exactly the workability, water ratio, and cement content required. I am glad to see this paper in the records of the Society. All that is needed is to keep in mind the limitations of the method and I think it will be found extremely valuable.

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[1] Director of Research, Portland Cement Assn., Chicago, Ill.

MESSRS. R. B. YOUNG[1] AND H. C. ROSS[2] (*by letter*).—The simplicity of Mr. Lyse's constant water method of designing concrete mixtures makes an immediate appeal to anyone having much of this work to do. The writers, being in this category, have gone to some trouble to examine the method in the light of the accumulated experience and data at their disposal from the extensive operations and experiments of the Hydro-Electric Power Commission.

The field and laboratory experience of the Hydro-Electric Power Commission of Ontario indicates that the constant water method is approximately correct within certain limits, but to maintain a constant consistency it is necessary to increase the water content per unit volume of concrete as the richer mixes are approached. Fortunately the range within which the constant water method may be applied with sufficient accuracy for most purposes is that which includes the mixes commonly used in concreting practice.

In a recent investigation on a set of mixes in which the gradation of the aggregates and the consistency were kept constant, the variation between the water requirements for mixes having cement-water ratios of 1.21 and 1.76 by weight, respectively, amounted to 6 lb. per cu. yd. of concrete. As the richness of the mix was increased beyond this point, a decided increase in water became necessary to maintain the consistency. A mix having a cement-water ratio of 2.2 required an increase of 33 lb. of water per cubic yard over the 1.21 cement-water ratio mix.

Table II of the paper gives the results of tests on nine different aggregates used in mixes with cement-water ratios varying from 1.25 to 2.25. Our experience leads us to believe that the constant water method of design is not sufficiently accurate to be used over such a wide range of mixes but should be applied only within reasonable limits on either side of the value obtained in the trial batch.

The method of designing concrete mixtures used by the Hydro-Electric Power Commission of Ontario has been first to establish experimentally the water-cement ratio curve for the cement and aggregates in question using a ratio of fine to coarse aggregate that experience or test has shown would give a proper workability, then by calculation from the data obtained in establishing the water-cement ratio curve, determine the water-cement ratio, cement content and unit weight of a concrete meeting the strength requirements sought. From then on it is a very simple matter to work out the proportions for any sized batch. This method has been used on dozens of different jobs, using many different types of aggregates and for concrete totalling well over a million cubic yards, and our experience has been that seldom do the proportions thus worked out have to be altered when first used in the field unless there has been a marked change in the character of the material used.

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MR. INGE LYSE[1] (*author's closure by letter*).—The author is pleased to note the favorable comments made by those who discussed this paper Since any method for designing concrete mixes gives only approximate values for field conditions, final adjustments have to be made on the job. The method of design should therefore be considered only as a convenient tool for the calculation of the approximate quantities of materials for given conditions. The proposed method has it advantage in its great simplicity and its fairly accurate results. Both the straight-line strength relation and the constant water requirement for a given consistency hold only within certain limits, which however, fortunately enough, cover the range of practically all concrete mixes used in present-day design. The proposed method of design has been used exclusively at the Lehigh University since January, 1930. The strength of the concrete has varied from 1000 to 6000 lb. per sq. in. and no difficulty has ever been encountered.

It has been called to the author's attention that the Swiss concrete investigator, Prof. J. Bolomey,[2] as early as 1927, had proposed the use of a straight-line relation between the cement-water ratio and the strength of the concrete, and that other European investigators have supported this proposal. For the sake of simplicity and the better understanding of the fundamentals of concrete making it is hoped that the cement-water ratio will soon be generally accepted as the criterion for the strength giving qualities of the concrete.

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[2] "Durcissement des Mortiers et Betons," *Bulletin Technique* de la Suisse Romande, Nos. 16, 22 and 24 (1927).

VOLUME CHANGES OF AN EARLY-STRENGTH CONCRETE

By E. R. Dawley[1]

Synopsis

This investigation consisted of a study of the changes in length accompanying changes in the temperature and moisture content of concrete specimens of various mixes and consistencies when made with ordinary portland cement and when made with a certain early-strength portland cement. Since the early-strength portland cement was known to produce concrete with a higher 28-day compressive strength than ordinary portland cement, and since rich mixes usually have shown less volume constancy than lean mixtures, it was supposed that for specimens of equal strength, those made with the early-strength cement would be more durable because of the smaller volume change.

The compressive strengths, the coefficients of thermal expansion, the coefficients of moisture expansion, and the absorption were determined for the various kinds of concrete studied. No effort was made to determine the volume change during the first 28 days caused by hydration of the cement.

The early-strength cement produced stronger concrete than the ordinary portland cement in equivalent mixes at ages of 3 and 28 days. The water-cement ratio - strength relation for the early-strength cement is of a different character from that of ordinary portland cement.

The coefficient of thermal expansion proved to be more affected by the kind of coarse aggregate used than by the kind or amount of cement.

The coefficient of moisture expansion increased with increased cement content. For concretes of equal 3-day compressive strength the coefficients for the early-strength concrete were smaller. For equal 28-day strengths the coefficients of the early-strength specimens were higher where limestone coarse aggregate was used but the kind of cement made no difference in the coefficients when sandstone aggregate was used. Wet mixes (7-in. slump) absorbed more water than dry ones (2-in. slump). Limestone concrete specimens absorbed more water than sandstone specimens. Specimens made with the early-strength cement absorbed less water than those made with ordinary portland cement.

Freezing-and-thawing tests indicated that specimens made with the early-strength cement were more durable than those made with ordinary portland cement.

Introduction

Volume Changes of an Early-Strength Concrete:

Past investigations on the volume change of concrete have shown that ordinary portland-cement concrete may change its length and shape for one or more of the five following reasons:

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1. *Hydration of the Cement.*—If fresh concrete is maintained in a moist environment, the length will increase rapidly to about 0.015 per cent at 24 hours and then increase slowly for a long time (perhaps several years). If at any time the concrete is permitted to dry out, a gradual shrinkage occurs which decreases in rate, the length remaining constant after about 250 days. For average mixes the shrinkage amounts to from 0.05 per cent to 0.09 per cent, with extreme cases as high as 0.18 per cent. The first expansion is accompanied by a temperature rise which accounts for a small part of the total expansion, while the contraction when drying out apparently may be completely accounted for by temperature and moisture changes.

2. *Change in Temperature.*—Concrete expands when heated and contracts when cooled. The coefficient of thermal expansion may vary from 0.0000031 to 0.0000065 in. per inch per 1° F. for ordinary concrete mixtures.

3. *Change in Moisture Content.*—Concrete expands when wetted and shrinks when dried. If the weight of water absorbed from the oven-dry to the saturated condition be taken as 100 per cent, then one one-hundredth of this amount represents 1 per cent of saturation. The coefficient of moisture expansion represents the unit change in length for 1 per cent of saturation and appears to vary from 0.0000015 to 0.0000032 in. per inch per 1 per cent of saturation for ordinary concrete mixtures.

4. *Elastic Change in Length Due to External Load.*—Concrete shrinks when compressed and expands when stretched in tension. The modulus of elasticity for ordinary mixtures varies from 2,500,000 to 6,500,000 lb. per sq. in.

5. *Plastic Change in Length Due to Steady External Load.*—Under steady load, concrete suffers a gradual deformation which remains after the load is removed. No general coefficients of this are now available.

Object of This Investigation:

It has been found that rich mixtures undergo greater volume change than lean ones. Moreover, a certain brand of early-strength portland cement was known to give consistently higher strength concrete than ordinary portland cement in mixtures of the same proportions. The object of this investigation was to determine whether or not a comparatively lean mixture using the early-strength cement would produce concrete equal in strength to a richer mixture of ordinary cement concrete and at the same time be superior as to volume constancy.

The volume changes measured in this investigation were confined principally to changes caused by varying the temperature and the moisture content. The specimens were 4 by 6 by 24-in. concrete beams molded in water-tight metal forms. Two pieces of 7-mm. glass tubing were inserted 20 in. apart, symmetrically placed on the center line and projecting slightly above the top surface of the concrete. These rods served as targets for measuring the gage length with an optical comparator.

The effect on the volume change of concrete of each of the following variables was studied:

1. *Cement.*—Ordinary portland cement, hereinafter designated cement P, and an early-strength portland cement, hereinafter designated cement E.
2. *Coarse aggregate.*—Sandstone and limestone.
3. *Richness of mix.*—Mixtures containing 1.0, 1.33, 1.67, 2.0, and (for cement P only) 2.25 barrels of cement per cubic yard.
4. *Consistency of concrete.*—Each of the above mixtures with the consistency indicated by 2-, 4-, and 7-in slumps.
5. *Temperature.*—(*a*) Specimens dry, (*b*) specimens wet.
6. *Moisture content.*—Oven-dry to saturated condition.

MIXES STUDIED

Two kinds of specimens were made: Six volume-change specimens consisting of 4 by 6 by 24-in. beams described above were made up for both a portland cement and an early-strength cement for each condition of richness of mix and of consistency mentioned above and using both sandstone and limestone aggregates, with the exception that only portland cement was used for the richest mix. Strength specimens consisting of twelve 6 by 12-in. cylinders were made for each group of six beams.

MATERIALS

Cements.—Two kinds of cements were used: Cement P an ordinary portland cement, and cement E an early-strength portland cement. The following are the characteristics of the two kinds of cements used, both of which meet the requirements of the Society's specifications.

	CEMENT P	CEMENT E
Fineness (percentage retained on 200-mesh sieve)	13.10	2.2
Normal consistency	25.0	26.5
Soundness	O.K.	O.K.
Time of set:		
Initial	2 hours, 30 minutes	2 hours, 20 minutes
Final	4 hours, 20 minutes	4 hours, no minutes

	Cement P	Cement E
Tensile strength, lb. per sq. in.:		
7 days	312	....
28 days	393	....
24 hours	....	330
72 hours	....	417
Compressive strength, lb. per sq. in.:		
24 hours	....	3300
72 hours	....	3800
Specific gravity	3.12	3.12

Fine Aggregate.—The fine aggregate was a clean, siliceous sand obtained from the Kansas River near Wamego, Kans., with the following physical properties:

Gradation factor (fineness modulus)	2.87
Weight, dry and loose, lb. per cu. ft.	105
Weight, dry and rodded, lb. per cu. ft.	112

Coarse Aggregate.—The sandstone was obtained from Lincoln County, Kans., and consisted of sand particles cemented together with calcium carbonate. The limestone was of a good grade obtained from Moline, Kans. The grading of the stone was as follows:

Passing 1½-in. sieve, retained on ¾-in. sieve	60 per cent by weight
Passing ¾-in. sieve, retained on No. 4 sieve	40 per cent by weight

Design of Mix.—The proportions of the mixtures were so taken that the absolute volumes of the sand and cement equaled 125 per cent of the voids in the stone. Table I shows the actual proportions of each mix from which the specimens were made.

Preliminary trial mixes were made to determine the proportions required to give a 4-in. slump with each cement factor and still have the absolute volumes of the cement plus sand equal to 125 per cent of the voids in the stone. The specimens with 2- and 7-in. slumps were made using the proportions computed for the 4-in. slumps but varying the quantity of mixing water to produce the required slump. Slight variations in the yields of the various batches account for the difference between the nominal and actual cement factors in Table I. The water-cement ratio, Table I, is computed on the basis of the actual quantities of cement and water entering the mix, no allowance being made for water which escaped from the cylinders after molding. All proportions are based on dry materials.

General Procedure

The concrete was mixed 1½ minutes in a power mixer of 3.5 cu. ft. capacity. A day's run consisted of 12 beams and 24 cylinders mixed in four batches, each batch weighing about 375 lb. The

TABLE I.—PROPORTIONS OF MIXTURES.

Cement Factor		Slump, in.	Mix, by volume			Water-Cement Ratio, by volume	Cement	Coarse Aggregate
Nominal	Actual		Cement	Sand	Stone			
1.00	1.03	2	1.00	3.07	4.84	1.123	P	sandstone
1.00	1.04	4	1.00	3.07	4.84	1.187	P	sandstone
1.00	1.03	7	1.00	3.07	4.84	1.291	P	sandstone
1.00	1.02	2	1.00	3.07	4.84	1.039	E	sandstone
1.00	1.03	4	1.00	3.07	4.84	1.102	E	sandstone
1.00	1.00	7	1.00	3.07	4.84	1.208	E	sandstone
1.00	1.06	2	1.00	2.97	4.84	1.017	P	limestone
1.00	1.05	4	1.00	2.97	4.84	1.099	P	limestone
1.00	1.03	7	1.00	2.97	4.84	1.180	P	limestone
1.00	1.05	2	1.00	2.97	4.84	0.955	E	limestone
1.00	1.04	4	1.00	2.97	4.84	1.027	E	limestone
1.00	1.03	7	1.00	2.97	4.84	1.099	E	limestone
1.33	1.40	2	1.00	2.16	3.68	0.881	P	sandstone
1.33	1.39	4	1.00	2.16	3.68	0.932	P	sandstone
1.33	1.36	7	1.00	2.16	3.68	0.964	P	sandstone
1.33	1.39	2	1.00	2.16	3.68	0.801	E	sandstone
1.33	1.36	4	1.00	2.16	3.68	0.868	E	sandstone
1.33	1.35	7	1.00	2.16	3.68	0.901	E	sandstone
1.33	1.40	2	1.00	2.00	3.68	0.768	P	limestone
1.33	1.39	4	1.00	2.00	3.68	0.830	P	limestone
1.33	1.38	7	1.00	2.00	3.68	0.861	P	limestone
1.33	1.39	2	1.00	2.00	3.68	0.736	E	limestone
1.33	1.38	4	1.00	2.00	3.68	0.753	E	limestone
1.33	1.38	7	1.00	2.00	3.68	0.800	E	limestone
1.67	1.74	2	1.00	1.57	2.93	0.715	P	sandstone
1.67	1.74	4	1.00	1.57	2.93	0.755	P	sandstone
1.67	1.73	7	1.00	1.57	2.93	0.780	P	sandstone
1.67	1.75	2	1.00	1.57	2.93	0.671	E	sandstone
1.67	1.74	4	1.00	1.57	2.93	0.709	E	sandstone
1.67	1.73	7	1.00	1.57	2.93	0.767	E	sandstone
1.67	1.72	2	1.00	1.52	2.93	0.658	P	limestone
1.67	1.69	4	1.00	1.52	2.93	0.696	P	limestone
1.67	1.69	7	1.00	1.52	2.93	0.735	P	limestone
1.67	1.70	2	1.00	1.52	2.93	0.639	E	limestone
1.67	1.70	4	1.00	1.52	2.93	0.664	E	limestone
1.67	1.68	7	1.00	1.52	2.93	0.715	E	limestone
2.00	2.07	2	1.00	1.17	2.41	0.631	P	sandstone
2.00	2.06	4	1.00	1.17	2.41	0.665	P	sandstone
2.00	2.05	7	1.00	1.17	2.41	0.678	P	sandstone
2.00	2.08	2	1.00	1.17	2.41	0.588	E	sandstone
2.00	2.08	4	1.00	1.17	2.41	0.623	E	sandstone
2.00	2.07	7	1.00	1.17	2.41	0.650	E	sandstone
2.00	2.10	2	1.00	1.12	2.47	0.567	P	limestone
2.00	2.10	4	1.00	1.12	2.47	0.599	P	limestone
2.00	2.08	7	1.00	1.12	2.47	0.631	P	limestone
2.00	2.11	2	1.00	1.17	2.41	0.548	E	limestone
2.00	2.09	4	1.00	1.17	2.41	0.578	E	limestone
2.00	2.07	7	1.00	1.17	2.41	0.610	E	limestone
2.25	2.35	2	1.00	0.98	2.16	0.565	P	sandstone
2.25	2.35	4	1.00	0.98	2.16	0.593	P	sandstone
2.25	2.32	7	1.00	0.98	2.16	0.626	P	sandstone
2.25	2.31	2	1.00	0.90	2.13	0.535	P	limestone
2.25	2.32	4	1.00	0.90	2.13	0.563	P	limestone
2.25	2.29	7	1.00	0.90	2.13	0.581	P	limestone

cylinders, with the exception of the 90-day cylinders which were cast in pasteboard molds and capped with a mixture of plaster of Paris and neat cement, were molded and capped according to the Society's Standard Methods of Making Compression Tests of Concrete (A.S.T.M. Designation: C 39 – 27).[1] The beams were molded in forms of No. 22 gage galvanized iron reinforced with a $\frac{1}{4}$-in. steel rod around the top. These forms were tapered, being $\frac{1}{8}$ in. wider at the top than at the bottom, to facilitate withdrawal of the specimens. Flexible metal shims were used at the ends to permit free longitudinal expansion of the specimens. The concrete was placed in these forms in layers and tamped with a 5-pronged tamper in a manner similar to that used in making the cylinders. The top was leveled off with as little working as possible and two glass rods inserted symmetrically 20 in. apart to serve as targets for the length measurements. To prevent evaporation, the top surfaces of the beam specimens were covered with flat pieces of heavy roofing paper perforated in three places to permit the glass rods and a thermometer to project through.

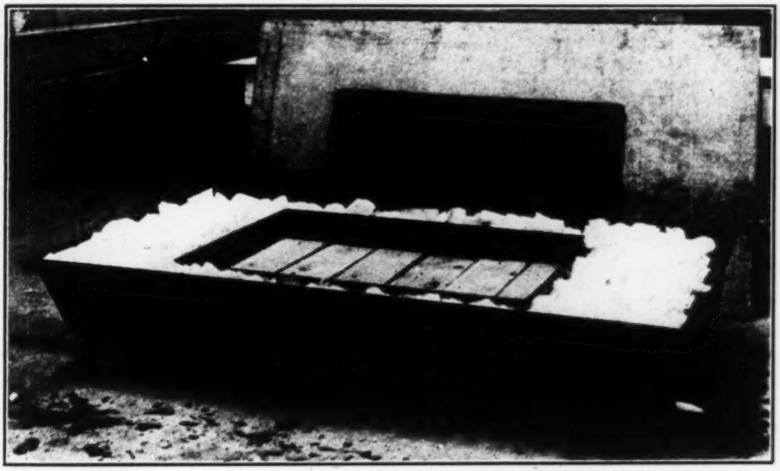

FIG. 1.—Specimens in Place Surrounded by Ice in the Tank.

All beam specimens were removed from the forms at 24 hours, weighed, and the length measured to the nearest ten thousandth of an inch.[2] The specimens were cured in a moist room at 70° F. and practically 100 per cent relative humidity for 13 days. After this they were allowed to dry in laboratory air for 14 days. Tests were begun on 28-day old specimens as follows:

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[1] 1930 Book of A.S.T.M. Standards, Part II, p. 143.

[2] For a complete description and illustration of the optical comparator used and the method of taking the measurements see the paper by C. H. Scholer and E. R. Dawley, "Volume Change of Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. 30, Part II, p. 753 (1930).

Volume Change Dry.—Three specimens from each group, or 162 specimens in all, were used in this test. The specimens were maintained in a so-called dry condition during this test. Temperatures were maintained constant by placing the specimens in a form lined and covered with celotex. The lengths and weights were determined at each of the following temperatures: 34, 60, 90, 120, and 150° F. For the 34° F. test, three portland-cement specimens and three early-strength specimens were placed in a large tank which was surrounded by a mixture of ice and salt, Fig. 1. The temperature was determined by thermometers placed in mercury wells in the center of the specimens The other temperatures were obtained by surrounding the tank with water at the desired temperatures. During this series of tests, specimens usually lost weight. In computing the thermal coefficient of expansion, the change in length was corrected by an amount corresponding to the measured change in per cent saturation.

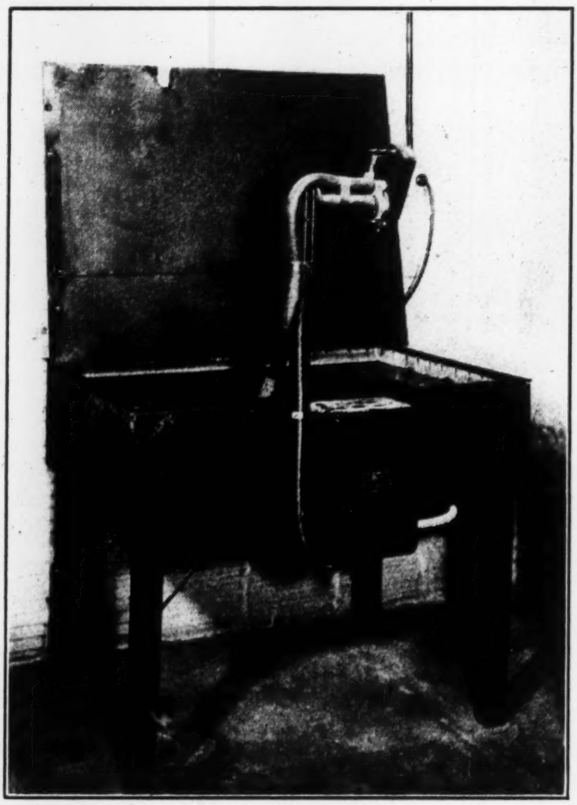

FIG. 2.—Specimens Immersed in Water.

Volume Change Wet.—This test was carried out on the remaining 162 specimens as above described, except that the specimens were immersed in water during the entire test. The higher temperatures 60, 90, 120, and 150° F. were obtained in a tank equipped with thermostatically controlled electric heating elements, Fig. 2. These specimens usually gained weight slightly, due to the absorption of moisture. In computing the thermal coefficient of expansion for these specimens, correction was made for the change in length corresponding to the measured change in the percentage of saturation.

TABLE II.—RESULTS OF STRENGTH TESTS MADE ON CONCRETE.

Note.—Each tabular value represents the average of three specimens except where otherwise indicated.

Cement Factor	Cement		Compressive Strength, lb. per sq. in.					
			Sandstone			Limestone		
			2-in. Slump	4-in. Slump	7-in. Slump	2-in. Slump	4-in. Slump	7-in. Slump
1.00	P	*Water-cement ratio*	*1.123*	*1.187*	*1.291*	*1.017*	*1.099*	*1.180*
		3 days	830	661	495	1188	1098	951
		7 days	1223	1122	978	1804	1583	1395
		28 days	2202	1954	1698	2607	2308	2137
		90 days	3100	2805	2441	3547	3184	3363
1.00	E	*Water-cement ratio*	*1.039*	*1.102*	*1.208*	*0.955*	*1.027*	*1.099*
		3 days	2191	2219	1407	3035	3031	2064
		7 days	2837	2740	1916	3537	3443	2605
		28 days	3655	3236	2472	3950	4330	3230
		90 days	4308	3321	3136	5458	5200	3855
1.33	P	*Water-cement ratio*	*0.881*	*0.932*	*0.964*	*0.768*	*0.830*	*0.861*
		3 days	1095	1192	1177	2132	2017	1528
		7 days	1836	1713	1923	2898	3138	2532
		28 days	2999	2608	2969	3913	4294	3729
		90 days	4391	3939	4463	5530	5670	5079
1.33	E	*Water-cement ratio*	*0.801*	*0.868*	*0.901*	*0.736*	*0.753*	*0.800*
		3 days	3730	2986	2906	4495	3856	3118
		7 days	4438	3817	3714	4846	4306	4422
		28 days	5242	4437	4187	5503	5673	5226[a]
		90 days	5105	4636	4085	6309	6333	5296
1.67	P	*Water-cement ratio*	*0.715*	*0.755*	*0.780*	*0.658*	*0.696*	*0.735*
		3 days	2166	1725	1354	2561	2402	2136
		7 days	2986	2844	2052	3456	3335	3153
		28 days	4159	4165	3291	4222	4220	4317
		90 days	5294	5217	4310	5071	5731	5495
1.67	E	*Water-cement ratio*	*0.671*	*0.709*	*0.767*	*0.639*	*0.664*	*0.715*
		3 days	4545	3511	3376	4181	4643	4676
		7 days	5227	4642	4067	5016	5148	5279
		28 days	5925	5265	4945	5690	5194	5898
		90 days	5729	5047	4242	6491	5046	6285
2.00	P	*Water-cement ratio*	*0.631*	*0.665*	*0.678*	*0.567*	*0.599*	*0.631*
		3 days	2354	1984	1629	3117	3366	2561
		7 days	3148	3196	3120	3883	4350	3386
		28 days	5013	4990	4480	5017	5624	5042
		90 days	4624	6717	4900	6639	6261	6591
2.00	E	*Water-cement ratio*	*0.588*	*0.623*	*0.650*	*0.548*	*0.578*	*0.610*
		3 days	3952	3886	3726	5230	5097	4160
		7 days	5217[a]	5648	4507	5432	5840	5123
		28 days	5666[a]	5588	5207	6027[a]	6584	6060
		90 days	5129[b]	5588	4920	5465	6261[a]	5769
2.25	P	*Water-cement ratio*	*0.565*	*0.593*	*0.626*	*0.535*	*0.563*	*0.581*
		3 days	3199	3310	2655	3666	3098	3032
		7 days	4714	4584	3909	4685	4511	4408
		28 days	6237	6060	5523	5732	5584	5592
		90 days	7092[a]	7431	6462	7239[a]	6741	6556

[a] Average of 2 specimens.

[b] One specimen.

Volume Change with Change in Moisture Content.—This test was run on the 162 specimens from the tests described under "Volume Change Dry." The specimens were dried in a thermostatically controlled oven maintained at 110 to 120° F. until the weight became constant at which time the length was measured. This length was used as the datum to which changes in length were referred. The specimens were then stored in laboratory air and length and weight measurements taken occasionally until the change was small. The specimens were then placed in the moist room and measurements continued intermittently until the change was small. The specimens were then placed in water and the weights and lengths again measured until the weight was constant.

During this test the temperature of the specimens varied somewhat. The measured changes in length were therefore corrected by applying the thermal coefficient of expansion for a temperature change corresponding to the difference between the observed temperature and the temperature of the specimen after it had been removed from the oven and allowed to return to room temperature.

Strength Tests.—The cylinders were removed from the molds at 24 hours and placed in a moist room maintained at a temperature of 70° F. The 3-, 7-, and 28-day specimens were removed from the moist room and tested in compression in a moist condition. The 90-day specimens were removed from the moist room at 28 days and allowed to stand in laboratory air until tested.

TEST DATA

Nearly 600 pages of data were taken during this investigation and an effort has been made by the author to analyze these data and present the results of this analysis in the form of curves and tables. Since this analysis may not completely cover all possible interpretations of the data, an effort has been made to present the original data in so far as possible, corrected only for moisture and temperature. Plotted points are shown on all curves since in some cases the correlation is not perfect. The following relationships are illustrated and discussed in this analysis:

Strength tests, Table II.
Coefficient of thermal expansion, Table III.
Relation of coefficient of thermal expansion to compressive strength, Fig. 3.
Coefficient of moisture expansion, Table IV.
Relation of coefficient of moisture expansion to 3-day compressive strength, Fig. 4.
Relation of coefficient of moisture expansion to 28-day compressive strength, Fig. 5.
Relation of water absorbed to cement content, Fig. 6.
Relation of water absorbed to quantity of mixing water, Fig. 7.

Strength Tests:

The results of the strength tests are shown in Table II in which each value represents the average of three cylinders (except as noted).

It will be noted from the table that the gain in strength with age of the portland-cement concrete specimens was, in general, a normal gain. The tests of the early-strength concrete showed small increases between 28- and 90-day ages for the leaner mixes, and small losses in strength for the richer mixes. Since all 90-day strengths were determined upon specimens cast in pasteboard molds and capped with a mixture of plaster of Paris and neat cement, it is entirely possible that the experimental error might have caused the variations noted.

TABLE III.—THERMAL COEFFICIENT OF LINEAR EXPANSION OF THE VARIOUS MIXES.

Cement Factor	Cement	Condition at Test	Coefficient of Thermal Expansion, in. per inch per 1° F. (0.56° C.) × 10^6					
			Sandstone			Limestone		
			2-in. Slump	4-in. Slump	7-in. Slump	2-in. Slump	4-in. Slump	7-in. Slump
1.00	E	Dry	5.22	4.63	5.09	3.33	3.23	3.53
	E	Wet	6.11	6.02	5.93	4.51	4.48	4.58
1.00	P	Dry	4.52	4.41	4.91	3.21	3.44	3.26
	P	Wet	6.06	5.68	5.92	4.60	4.69	4.69
1.33	E	Dry	5.13	5.73	5.16	3.49	3.72	3.52
	E	Wet	6.16	5.64	5.87	4.50	4.59	4.30
1.33	P	Dry	5.02	5.55	4.95	3.51	3.87	3.80
	P	Wet	5.99	5.73	5.98	4.63	4.97	4.70
1.67	E	Dry	5.78	5.51	5.60	3.84	3.99	3.87
	E	Wet	6.14	6.12	5.97	4.93	4.63	4.37
1.67	P	Dry	5.38	4.82	4.84	3.44	3.65	4.14
	P	Wet	6.25	6.02	6.10	4.40	4.86	4.94
2.00	E	Dry	5.05	6.50	5.79	4.14	3.12	3.72
	E	Wet	6.42	6.20	5.81	4.46	4.37	3.68
2.00	P	Dry	5.40	5.25	5.82	4.33	3.28	4.01
	P	Wet	5.94	6.40	6.35	4.70	4.71	4.72
2.25	P	Dry	5.41	5.35	6.44	3.95	4.10	4.18
	P	Wet	6.29	6.48	6.34	4.67	4.42	4.79

Other strength tests of this and other brands of early-strength portland cement for a period of over two years indicate a gradual increase in strength during that period.

The limestone was dry when used and absorbed some of the mixing water. The values of the water-cement ratio for the limestone concrete in Table II have all been corrected for this absorption. Even with this allowance made and taking into consideration the probable difference in strength caused by the difference in water-cement ratios, the limestone concrete proved to be stronger than the sandstone concrete at all ages; the increase amounting to as much as 50 per cent in the case of the average 3-day strength.

Curves showing the relation of water-cement ratio to compressive strength, which were plotted from Table II (but not included here for lack of space), are interesting for several reasons. First, a very good agreement was found to exist between the test results for portland-cement concrete and Abram's curve, $\frac{(14{,}000)}{7^{w/c}}$; the test results being in all cases slightly higher than Abram's curve. Second, the limestone concrete invariably proved to be stronger than the sandstone concrete. Third, the curves for the early-strength concrete proved to be an entirely different shape from those for portland-cement concrete. Instead of being convex downward as Abram's curve is, these curves are convex upward. If extended, these curves would intersect the portland-cement curves at water-cement ratios of approximately 0.5 and 1.2. Midway between these values the curves are as much as 2200 lb. per sq. in. apart in the case of the 2-in. slump and 3-day strength. For 28-day strengths and 2-in. slump the difference was about 1600 lb. per sq. in. For the 7-in. slump and 28-day strength the difference was only about 1000 lb. per sq. in.

The foregoing indicates that there is a fundamental difference between the early-strength cement and the ordinary portland cement even though both cements meet the same specifications.

Thermal Expansion:

The coefficients of thermal expansion of the various mixes are shown in Table III. All coefficients for dry specimens were corrected for changes in moisture content which occurred during the test. The coefficients were computed by the method of averages from the data. Each tabular value represents the mean slope of a line indicated by 15 plotted points.

An examination of Table III discloses the following:

1. The thermal coefficient of linear expansion is considerably larger for wet concrete than for dry concrete: the average difference is 16 per cent for the sandstone and 23 per cent for the limestone concrete.
2. The thermal coefficient of expansion is from 20 to 40 per cent larger for sandstone concrete than for limestone concrete of the same proportions.
3. The thermal coefficient increases slightly with increased cement content for the dry sandstone specimens, and a barely perceptible amount for the wet sandstone specimens.
4. There is practically no variation in the coefficient of thermal expansion with different values of the cement factor for both wet and dry limestone concrete.

5. There is no significant difference between the coefficients of thermal expansion for concretes made with cement E or with cement P.

In examining Table III it must be remembered that for the same cement factor the early-strength concrete was the stronger. The variation of the coefficient of thermal expansion with 28-day compressive strength is shown in Fig. 3. The observations made above apply here with one exception. In eleven of the twelve curves shown for the early-strength cement, the values of the coefficient of thermal expansion were less than those for the portland-cement concrete.

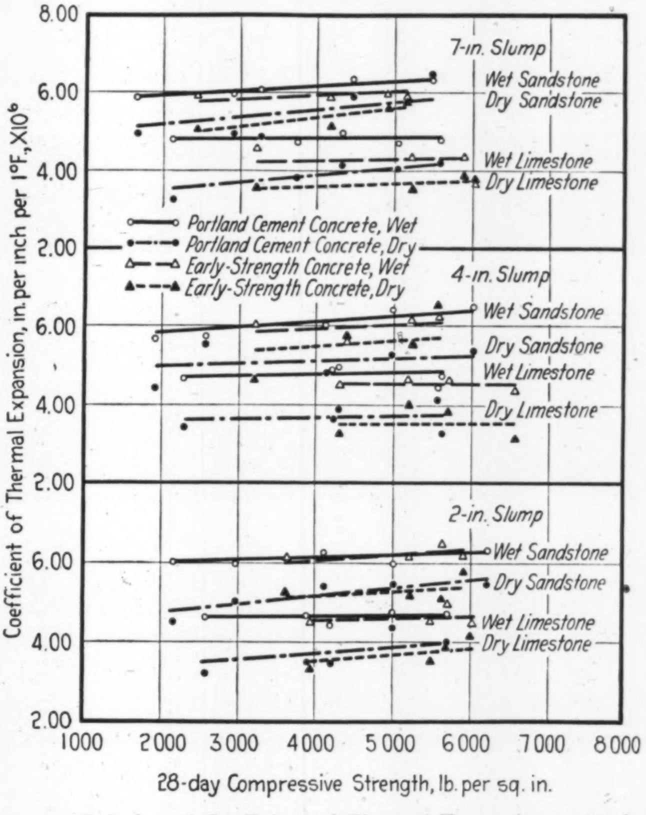

FIG. 3.—Relation of Coefficient of Thermal Expansion to 28-day Compressive Strength.

Coefficient of Moisture Expansion:

Table IV shows the coefficients of moisture expansion. Each value in the table represents the mean slope of the line representing that group of data. This assumes a straight-line variation for change in length with change in percentage of saturation which seemed justified after plotting the data.

While there are several apparently inconsistent values in Table IV, the following conclusions seem to be warranted:

1. There is a definite increase in the coefficient of moisture expansion with increased quantity of either kind of cement.

2. For equivalent mixes the early-strength cement produces concrete having a higher coefficient of moisture expansion than ordinary portland-cement concrete. The difference ranged from 20 to 65 per cent. The greater difference occurred with the cement factor of 2.0, where the average difference was 50 per cent.

TABLE IV.—COEFFICIENT OF MOISTURE EXPANSION.

Cement Factor	Cement	Coefficient of Moisture Expansion, in. per inch per 1 per cent of saturation, $\times 10^6$					
		Sandstone			Limestone		
		2-in. Slump	4-in. Slump	7-in. Slump	2-in. Slump	4-in. Slump	7-in. Slump
1.00	P	1.51	1.69	1.20	1.71	2.15	1.68
	E	1.80	[a]	1.39	2.07	2.73	2.24
1.33	P	1.70	2.07	1.38	1.78	2.38	2.79
	E	2.02	2.43	2.30	2.70	2.98	2.88
1.67	P	2.39	1.87	1.77	2.08	1.99	2.59
	E	3.41	2.31	2.25	2.91	2.70	3.75
2.00	P	1.50	1.43	1.77	2.32	2.04	1.85
	E	2.72	2.51	2.47	2.76	2.67	2.89
2.25	P	2.73	3.15	3.18	2.97	2.88	2.85

[a] All three of the targets broken.

3. Concrete made with limestone coarse aggregate has a slightly larger coefficient of moisture expansion than concrete made with sandstone coarse aggregate.

Figures 4 and 5 present data from which a comparison may be made on the basis of equal compressive strengths rather than on equivalent mixes. Examination of these curves indicates a definite increase in coefficients of moisture expansion with increase in both 3-day and 28-day compressive strengths. Figure 5 shows that for equivalent 28-day compressive strengths the early-strength limestone concrete has the largest coefficient in each case. However, the early-strength sandstone concrete has nearly the same coefficient as the ordinary portland-cement sandstone concrete. Figure 4 on the contrary, shows that for equivalent 3-day strength, the early-strength concrete has the lower coefficient of moisture expansion.

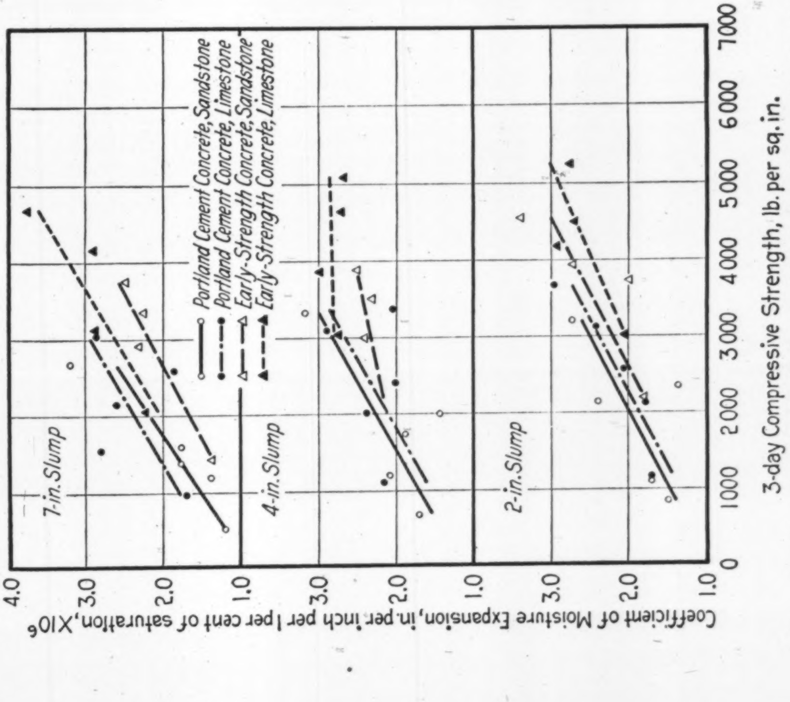

FIG. 4.—Relation of Coefficient of Moisture Expansion to 3-day Compressive Strength.

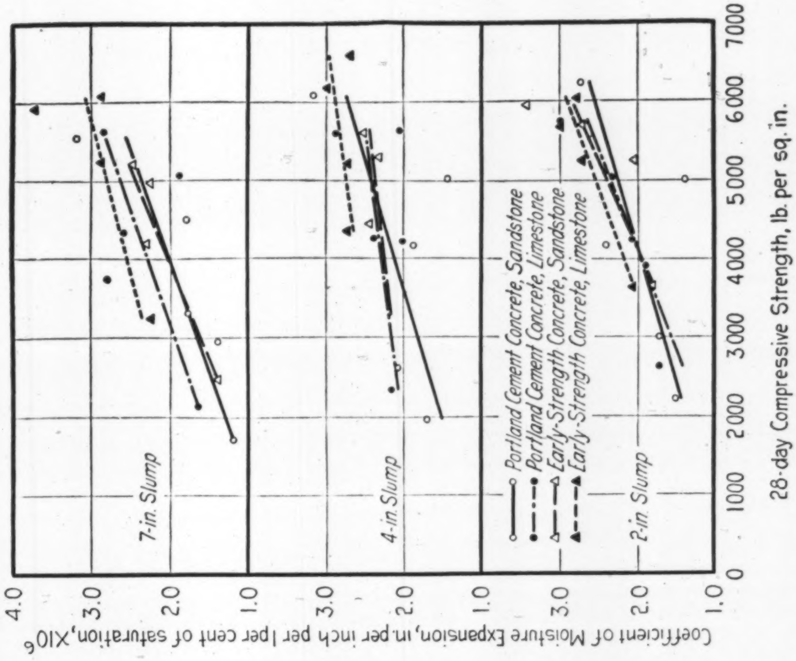

FIG. 5.—Relation of Coefficient of Moisture Expansion to 28-day Compressive Strength.

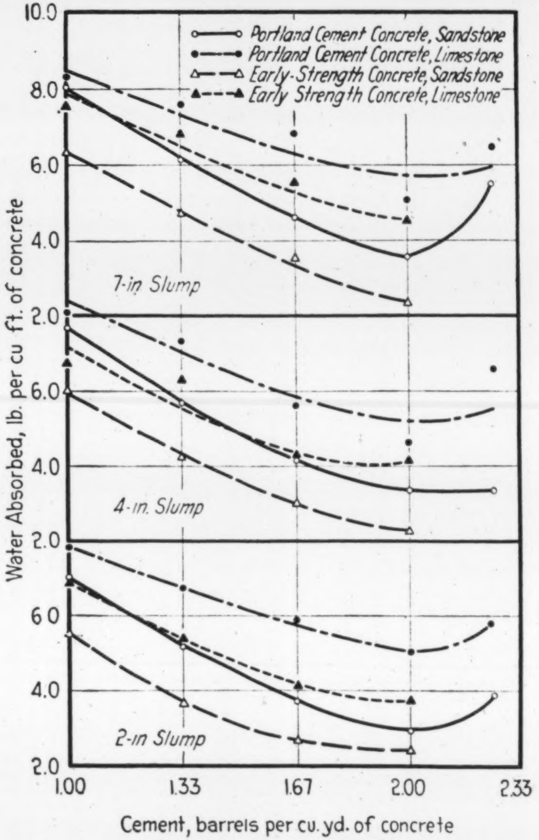

FIG. 6.—Relation of Water Absorbed to Cement Content.

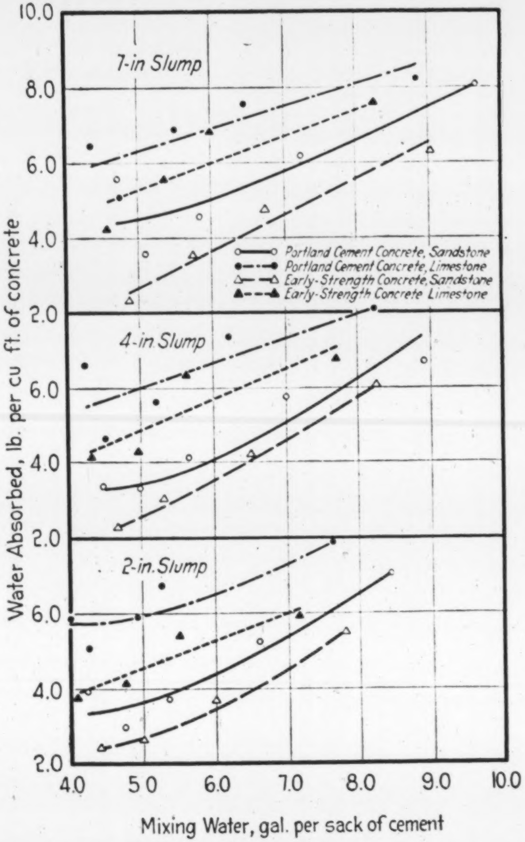

FIG. 7.—Relation of Water Absorbed to Quantity of Mixing Water.

Absorption:

Absorption is a rough measure of durability since durable concrete is usually quite impervious. Figure 6 shows the relationship between the quantity of water absorbed by the concrete from the oven-dry to the saturated state, and the quantity of cement in the mixture. It is apparent from these curves that water-tightness increases with the cement content, but at a decreasing rate up to a cement content of 2 barrels per cu. yd. The wetter mixes absorbed the more water, although the total variation was not great. Limestone concrete absorbed more water than sandstone concrete. Concrete made with cement E absorbed less water than that made with cement P.

Figure 7 shows the quantity of water absorbed, plotted against the original quantity of water in the mixture. This curve indicates a direct relationship between the quantity of water absorbed and the quantity originally placed in the mixture. Limestone concrete again absorbed more water than sandstone concrete, and early-strength concrete (cement E) absorbed less water than cement P concrete.

CONCLUSIONS

The early-strength cement produced more workable, stronger concrete with less mixing water than the ordinary portland cement.

The 3-day compressive strength of concrete made with the early-strength cement for all mixes was practically equal to the 28-day strength of the ordinary concrete.

The limestone coarse aggregate gave stronger concrete than the sandstone aggregate in equivalent mixes in all cases.

The compressive strength of concrete made with the early-strength cement varied with the water-cement ratio in a manner entirely different from that made with cement P. For the intermediate values of the water-cement ratio, the early-strength concrete was considerably stronger than the ordinary concrete at the ages of 3 days and 28 days. For the dry and wet mixes, however, the strengths tended to approach each other.

The coefficients of thermal expansion were essentially the same for mixes of the same proportions using either cement. For concretes of equivalent strength, however, the early-strength concrete had a slightly smaller coefficient.

The coefficient of thermal expansion was from 20 to 40 per cent larger for concrete having sandstone for the coarse aggregate than for that having limestone coarse aggregate. This coefficient also tended to increase somewhat with increased richness of mix when sandstone coarse aggregate was used, but showed no such indication when limestone coarse aggregate was used.

The coefficient of moisture expansion increased with increased quantity of either the early-strength or ordinary cement. For the same proportions of mix the coefficients for the early-strength concretes were from 20 to 65 per cent greater than for ordinary concrete. For concretes of the same 28-day compressive strengths, the early-strength concrete with limestone coarse aggregate had the larger coefficient, the difference for 3500 lb. per sq. in. concrete being 14 per cent. The coefficient was practically the same for the early-strength concrete and ordinary concrete where sandstone coarse aggregate was used. The coefficient of moisture expansion for the early-strength concrete was from 10 to 50 per cent less than that for the ordinary concrete, for concretes of the same 3-day compressive strength.

It was stated above that the kind of coarse aggregate caused variations in the thermal coefficient of 20 to 40 per cent, and the kind of cement caused variations in the moisture coefficient of from 20 to 65 per cent. From this, one might conclude that the kind of cement had the greater effect on the volume change. The fact is, however, that the kind of aggregate exerts the greater influence since the values of the thermal coefficient are about twice as large as the moisture coefficient.

Assuming a change from dry to saturated condition accompanying an increase in temperature of 100° F., sandstone concrete under conditions favorable to small volume change (2500 lb. per sq. in. compressive strength using portland cement) showed only 6 per cent less volume change than limestone concrete under the most unfavorable conditions (6000 lb. per sq. in. compressive strength using early-strength cement). When oven-dried and then soaked in water, wet mixes absorbed more than dry mixes. Limestone concrete absorbed more than sandstone concrete. The early-strength concrete absorbed less than ordinary concrete.

Tests made on limestone and sandstone specimens similar to those used in this investigation indicate that the thermal coefficient of expansion of the concrete is essentially that of the coarse aggregate itself.

Acknowledgments.—The author wishes to acknowledge the valuable assistance of Mr. C. H. Scholer in planning the tests and analyzing the data, and the assistance of Mr. D. C. Taylor, and Mr. H. C. Cowdery in taking and working up the data.

A RAPID METHOD OF DETERMINING THE SPECIFIC GRAVITY OF PIGMENTS AND POWDERS

By E. J. Dunn, Jr.[1]

Synopsis

This paper describes a method of determining the specific gravity of pigments and powders, based on the wetting of the particles by utilizing a dispersing agent and grinding with a mortar and pestle. This is an effective way of breaking down agglomeration and eliminating occluded air which are the main difficulties in the specific gravity test for powders. Some experimental results are reported.

The problem of thoroughly wetting pigments or powders has made its appearance in many fields of work. To obtain good dispersion of relatively coarse powders for elutriation purposes, C. A. Kline and J. Parrish[2] treated the powders under a reflux condenser for two hours in boiling methylated spirits or other selected medium. For similar reasons, W. M. Wiegel[3] agitated his suspensions with a dilute solution of NH_4OH in a blunging machine for one hour prior to elutriation. The Society[4] has designated the use of kerosine under vacuum for wetting powders in the determination of specific gravity. Paint manufacturers use selected oils and various special mills to give their desired degree of incorporation. In the study of the use of the turbidimeter[5] for testing the quality of paints in regard to the dispersion of particles in vehicles, a mortar and pestle were used to prepare some of the suspensions. From this investigation the thought came that this well-known way of incorporating pigments into vehicles could be applied to the determination of specific gravity. It developed that the specific gravity of a pigment or powder is easily determined by incorporating the powder into a vehicle so that all lumps are broken down, as nearly as possible, to individual particles, thereby eliminating occluded or entrained air. It has been the author's experience that both good wetting by the vehicle and good mechanical action on the mass are very necessary to obtain good incorporation. Grinding the pigment and vehicle as a pasty mass with a mortar and pestle is an excellent means of obtaining good incorporation. This is the basic idea in this method of determining specific gravity.

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[1] Research Laboratories, National Lead Co., Brooklyn, N. Y.

[2] C. A. Kline and J. Parrish, "Size of Particles with Special Reference to Pigments," *Journal*, Oil and Color Chemists Assn., Vol. VII, No. 45 (1924).

[3] W. M. Wiegel, "Size and Character of Grains of Nonmetallic Mineral Fillers," U. S. Bureau of Mines *Technical Paper 296* (1924).

[4] Standard Methods of Test for Specific Gravity of Pigments (A.S.T.M. Designation: D 153 – 27), 1930 Book of A.S.T.M. Standards, Part II, p. 345.

[5] E. J. Dunn, Jr., "The Turbidimeter in the Paint Industry," *Industrial and Engineering Chemistry*, Analytical Edition, April, 1932.

APPARATUS USED

A lipped porcelain mortar and a pestle are used for the incorporation. The capacity of the mortar is approximately 500 ml. The specific gravity flasks are made according to the Society's specifications for gravity flasks[1] except for the top being 22 mm. wide to aid transferring the suspension from the lipped mortar. The water bath is any simple pan that is deep enough for the immersion of the flasks to the upper part of the neck of the flasks. An accurate thermometer and balance should be used for this work. A good grade of powdered gum arabic is very necessary, also a dropping bottle that has the dropping pipette mounted in the rubber stopper. See Fig. 1.

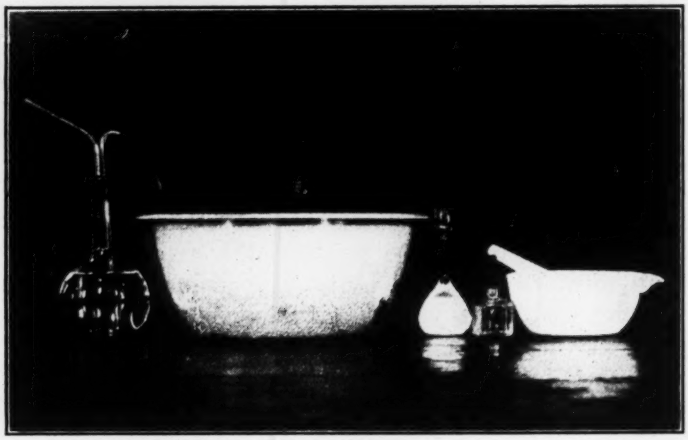

FIG. 1.—Apparatus for Use in Making Tests.

METHOD

The flasks all have to be calibrated for use. It is necessary to check the weights of the flasks empty and also filled to the 100-ml. mark with gum arabic water. The weights of the flasks filled with gum arabic water should be obtained for approximately every 3° C. over a range of about 20 to 32° C. A smooth curve drawn through these points will give the weight for any normal room temperature so that gravities may be run at various room temperatures, the weight of flask plus gum arabic water being taken from the curve. The amount of powdered gum arabic in the water is exactly 1 g. per 100 cc. of distilled water as 1 g. of powdered gum arabic is used in incorporating the pigment into the water.

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[1] Standard Methods of Test for Specific Gravity of Pigments (A.S.T.M. Designation: D 153 – 27), 1930 Book of A.S.T.M. Standards, Part II, p. 350.

For white leads, 20 g. of the dry pigment are used for the determination. Pigments whose specific gravities are much less and bulk quite a bit require only about 8 g. The accurately weighed pigment plus 1 g. of powdered gum arabic are carefully transferred to the mortar. Two or three cubic centimeters of distilled water are added and the mass ground into a paste. More distilled water is added if necessary to obtain a smooth paste. The paste is worked about four minutes and diluted with about 25 to 30 cc. of distilled water and mixed to uniformity. The suspension is then transferred to a specific-gravity flask, the mortar being thoroughly washed with a slow-delivery wash bottle. After the suspension is in the specific-gravity flask, there should still be about 25 ml. of distilled water to be added. This 25 ml. is added to the flask very slowly and without stirring up the suspension into the clear supernatant liquor. The flask is filled to the mark and placed in the water bath. On standing a few minutes, all the small entrained air bubbles come to the surface and may be drawn off with a small dropping pipette. After removal of the air bubbles, the flask is very accurately filled to the mark and placed in the water bath for fifteen minutes. It is then removed from the bath, the end point is checked, and the flask is carefully dried with a towel and weighed.

The same formula may be used for calculating the specific gravity as is designated by the Society:

$$\text{Specific gravity} = \frac{P \times S}{(P + K) - F}$$

where P = weight of pigment used;

S = specific gravity of gum arabic water;[1]

F = final weight of flask with pigment and gum arabic water; and

K = weight of flask filled with gum arabic water.

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[1] This may be obtained from the weight of the flask filled to the mark with distilled water. Then the ratio of the weight of gum arabic water to distilled water will give the specific gravity.

Some results obtained by this method are as follows:

	SPECIFIC GRAVITY
White lead	6.81
Titanium oxide	3.93
Basic lead sulfate	6.30
Zinc sulfide	4.16
Zinc oxide	5.59
Titanox B	4.22
Lithopone	4.29
Titanox C	3.26
High-strength lithopone	4.21

These figures are for the samples tested and should not be used to represent all samples of the pigments.

Gum arabic was used as the wetting agent for this work as it was found to be a good wetting medium for various pigments and powders, but the method could be standardized with some other suitable wetting agent. Specific gravity values have been obtained for several fillers and colors as well as a few other powders by this method and found satisfactory. The fact that an agent that deflocculates one powder well tends to deflocculate several powders has also been demonstrated in the recent work by Ryan, Harkins and Gans.[1]

This method requires approximately one hour for check determinations, after the flasks have been calibrated, which is a relatively short period for specific gravity determinations. It does not require the use of a vacuum pump. Suspensions made by this method are very smooth and fluffy. Check determinations are practically always within 0.02 of a point which makes it a fairly accurate method.

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[1] L. W. Ryan, W. D. Harkins and D. M. Gans, "The Flocculation, Dispersion and Settling of Pigments in Relation to Adsorption," paper read at the New Orleans meeting of the American Chemical Society, March 28, 1932.

DISCUSSION

Mr. P. H. Walker.[1]—I wonder why the author used 1 g. of powdered gum arabic with his pigment and then made up for it with water, instead of using a 1-per-cent solution of gum arabic. He determines the specific gravity of a 1-per-cent solution of gum arabic but then he adds 1 g. to somewhat less than 100 ml. of water. The method would be theoretically, at any rate, more accurate if he had used a 1-per-cent solution of gum arabic for his grinding medium rather than using the powdered gum arabic and water. He neglects the volume of the gum arabic.

Mr. E. J. Dunn, Jr.[2]—The object of using 1 g. of dry powdered gum arabic for rubbing up the paste is that it has a much better effect in regard to dispersing the particles of the pigment than if a 1-per-cent solution of gum arabic is used. The concentration of that 1 g. in approximately 2 ml. of water produces a very heavy paste, and it is sticky, so that when you are working with a fairly large pestle you are getting real incorporation, whereas with plain 1-per-cent solution you do not get the same result. We worked suspensions both ways and prefer the dry powder.

(*By letter*).—Since the presentation of the paper, we have determined the specific gravity of gum arabic water of various strengths. Results were plotted so that specific gravity could be read from the curve. Carrying the figures out to the fifth place, by reading them from the curve, the variation in specific gravity from a 1-per-cent to 1.03-per-cent solution is 1.00355 to 1.00366. The difference of 0.00011 is very small and had to be obtained by running specific gravities for percentages both higher and lower than 1 to 1.03.

In making determinations of specific gravity, the volume of water displaced is practically always just under 3 ml. This is equivalent to the bulk of a sample that can be conveniently placed on a tared watch glass. If it is desired to make the test more accurate, that is, nearer to the theoretical value, the figure of 1.00355 should be used in the calculations and a weight of 0.985 g. of gum arabic used for incorporating the pigment so that the solution would more nearly approach a 1-per-cent solution.

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[1] Chemist, U. S. Bureau of Standards, Washington, D. C.

[2] Research Laboratories, National Lead Co., Brooklyn, N. Y.

MR. P. S. ROLLER.[1]—I should like to call attention to the effectiveness of a 0.25-per-cent solution of saponin in 50-per-cent alcohol as a dispersing agent. It occurs to me that this solution may well require only a simple shaking of the pigment suspension in order to liberate the air bubbles.

MR. H. A. NELSON.[2]—Our laboratory has used saponin for a number of years for preparing pigment dispersions. It is a most effective material for that purpose. It is much more effective than gum arabic and could undoubtedly be used for the specific gravity determinations.

MR. DUNN.—There seems to be a different phenomenon produced in dispersion in making microscopic slides. In our trial work in this method we had tried the use of both gum arabic and saponin together and found that it was inclined, due to its soapiness, to produce a lot of bubbling and frothing that we thought was troublesome, and for that reason we did not use it.

MR. C. R. BOGGS.[3]—I should like to inquire as to whether any work has been done relative to the effect of a dispersing agent on the gravity of the pigment or powder. Normal dispersion is explained by a physical or slight chemical reaction between the particle and the dispersing agent, and there is a great deal of evidence to show that one end of the molecule of the dispersing agent hitches to the particle surface and the other end of the molecule is dissolved in the liquid. Consequently, particles surrounded by an adsorbed layer of dispersing agent are in a different condition than the same particles in water alone, and this difference might affect the specific gravity. I should like to know if this effect was considered and, if so, what is the amount?

MR. DUNN.—There is no way we could really judge that phenomenon but actually I do not see that absorption could affect the test, considering the molecular volume calculation. According to the surface of 1 g. of pigment, the adsorbed layer of water would amount to probably less than 0.2 mg. per gram of pigment in the large weight of water used—which is very small. If there is a slight concentration of the gum arabic at the surface of the particle it should not affect the gravity because the gum arabic is all in there and dissolved. In comparison with the amount of gum arabic that is in solution I should expect it to be almost a trivial amount that would be concentrated at the surface of the particles when it is calculated out as a molecular film, the concentration of which would also be hard to determine.

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[1] Associate Chemist, U. S. Bureau of Mines, Nonmetallic Minerals Experiment Station, New Brunswick, N. J.

[2] New Jersey Zinc Co., Palmerton, Pa.

[3] Vice-President, Simplex Wire and Cable Co., Boston, Mass.

MR. F. C. SCHMUTZ.[1]—Mr. Dunn suggested that although a surface reaction takes place this would not affect results. Might we not take advantage of this fact by definitely suspending this pigment in a reactive medium, as for example, some basic pigments in linseed oil and then determine the specific gravity of the resulting system. With a knowledge of the specific gravity of the original suspending medium, the specific gravity of the pigment could then be calculated. In such a procedure complete contact between the pigment and liquid would be assured and the introduction of a third component to the system, as water, eliminated.

MR. DUNN.—Actually it is really gum arabic in water that is the dispersing medium and amounts to almost the same thing, except you suggested a different vehicle.

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[1] New Jersey Zinc Co., Palmerton, Pa.

AN EXAMPLE OF LONG-TIME SERVICE OF BAKED ENAMEL COATING ON WATER PIPE

By A. H. Sabin[1]

Varnish enamels are made of a drying oil compounded with a resin or a resin-like substance, and are often hardened in ovens. For convenience they sometimes are made with the addition of a volatile ingredient, as turpentine, but this is not essential. Varnishes of this type harden by oxidation, taking up oxygen from the air. This operation is hastened by heat. Some varnishes will not harden properly, if at all, at ordinary temperatures. Oxidation is often accompanied by shrinking, which may produce pores; but when heat is used the film is maintained in a liquid condition, which not only makes it continuous but tends to cause it to adhere uniformly and completely to the solid surface to which it has been applied, and to force the perfect and desirable oxidation of a film which resists such chemical change at ordinary temperatures, and permits the use of more stable and resistant compounds in the film. All this has long been known, and the process has been applied to small objects for many years; forty years ago the surface plates of sewing machines were probably the largest of these. Black enamels, which seem to be the best, owe their color to asphaltum, a fusible mineral much like a vegetable resin in its physical qualities, and soluble, hot, in linseed oil. In the formula book of one of the oldest and best of American makers it was insisted that some Zanzibar or Benguela resin should be an ingredient, but these expensive things are now generally left out; but we now have in the mineral gilsonite a purer and better asphaltum than was then to be had.

In 1895 the city of Allegheny, Pa. (now Pittsburgh) built, as part of the city water supply, a steel pipe 10 miles long and 5 ft. in diameter, made of riveted plates ½ in. thick. The pipe was made in sections 25 ft. long weighing 5 tons each; lap-jointed and the sections field-riveted together. This pipe was coated with a varnish enamel baked on at 400° F. (205° C.) for 2 hours. The coating plant was in a large temporary building. Near one end was the dipping-tank, about 30 ft. deep and 6 or 7 ft. in diameter. The coating material, which to obviate fire risk contained no volatile matter like turpentine, was made elsewhere and brought in iron drums and emptied into the tank, which was heated by an exterior natural-gas furnace. Almost adjacent was the oven, a brick structure, nearly

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[1] Consulting Chemist, National Lead Co., New York City.

30 ft. high, made in four compartments, each to hold two pipe sections in a vertical position, the ovens opening by sliding doors at the top so that the pipes could be lowered into place. The pipe sections, new and clean but not pickled nor sand blasted, were dipped into the hot liquid in the vertical tank; after becoming hot the section was slowly raised, the adhering excess coating was allowed to drain as much as possible, then the pipe was quickly put into an empty space in the oven, where it rested on a trough from which the drip was recovered and put back into the tank. After baking two hours the section was lifted out and laid on skids; the inspector pounded it, when cold, with a $\frac{3}{4}$-in. iron rod and if no injury to the coating resulted it was accepted. The coating produced was not injured in the driving of red hot rivets.

It is generally agreed that asphaltum is a residue from the evaporation and polymerization of petroleum; the older chemists expressed their view by adding that it contained as a softening ingredient a more oil-like portion which they called petrolene, and a solid but oil-soluble part named asphaltene. Today chemists split up these ingredients more, and use more technical terms; but the old classification expresses facts to the ordinary user. A solution of a flexible asphalt in a volatile liquid dries, by evaporation, to an elastic coating; but in time the mineral-oil-like part goes off, leaving a loose, powdery residue. Gilsonite is a hard asphaltum; pieces of it appear like anthracite, it will never soften nor tend to adhere, and probably would be called by the older mineralogists pure asphaltene. It melts like a hard resin, and will then dissolve in hot oil, such as linseed oil. When we apply a thin film of such a compound it hardens by oxidation of the oil and we still have all the oil there as linoxyn, or something like it, and it still imparts elasticity to the coating. For some reason, asphaltum retards this oxidation; but in a hot oven the oxygen and the oxidizable oil are much more active chemically and the film hardens rapidly, that is in two or three hours, if the temperature is near 400° F. (205° C.), into a tough, smooth, hard and permanent enamel. The fact that heat is necessary to produce this oxidation agrees with the fact that it does not spontaneously oxidize further, to the destruction of the film, in ordinary use. Overbaking would make it brittle. But the softer asphalts, such as Trinidad, do not combine properly with linseed oil, and enamels made with them are more porous and perishable. Of course gilsonite is not chemically a resin, which is of vegetable origin, but in enamels it acts like a resin and if it is understood that no deception is intended it is not unfair to call it a mineral resin; it is as much like resin as the so-called synthetic resins now almost exclusively used, in varnish-making; and it is of unequaled durability. This was the nature of the compound, containing 50 to 55 per cent of linseed oil, used in coating the previously mentioned large pipes, forming a finished film 0.002 to 0.004 or 0.005 in. thick, which has lasted nearly forty years and is said, hopefully, to be good for thirty years more. It is as hard as marble, that is, about 3 on the mineralogists scale of hardness, on which felspar is 6 and quartz 7. It is so tough and adherent that a piece of ½-in. pipe coated with it may be bent, cold, into a coil 8 in. in diameter, and it will still withstand the five to ten per cent acid in a pickling bath for an hour or more.

Mr. J. H. Kennon, Managing Engineer of the Bureau of Water, of Pittsburgh, under date of January 6, 1932, says: "This pipe line is still in service and in good condition. To the best of our knowledge, the coating is in good condition with the exception that where the pipe line passes through 'cinder fill,' especially in the Borough of Sharpsburg, it was necessary to enclose approximately 1200 ft. of the pipe in reinforced concrete." In addition to this, Mr. William C. Donnan, District Superintendent, told the author in conversation that in one or two places the pipe was partly exposed and the coating had suffered from ordinary abrasion and these bare places had been painted; but not elsewhere. Mr. A. O. Doane, Senior Mechanical Engineer of the Metropolitan District Commission of Massachusetts, wrote on November 5, 1931, "I looked up the record of the pipe line in Pittsburgh while on a visit to that city a few years ago. It has certainly given good service."

In this same year (1895) about five miles of 40-in. steel pipe was built for the city of Cambridge, Mass. This was treated with the same coating. In the letter from Mr. Doane already quoted, he says about this pipe, "there was some trouble some years ago from electrolysis, due to stray current from the street railroad system, but that has been eliminated." Mr. T. W. Good, Superintendent of Water Works of Cambridge, has recently cut out a piece of this pipe, which showed it to be in very good condition. They are pumping a filtered and chlorinated water."

The year before these pipes were built, the city of Rochester, N. Y., built about fourteen miles of 38-in. steel pipe, which was coated in a nearly similar way. This coating was applied by rolling the pipe sections (which were 28 ft. long and weighed about 2½ tons each) in a horizontal trough-like tank containing the liquified coating material in much the same way that cast-iron pipe is coated with coal-tar; it was then baked in a vertical oven. This was a coating compounded of linseed oil and asphaltum, but instead of using gilsonite the asphaltum was Trinidad asphaltum or, partly, maltha, a residual asphaltum from the distillation of California petroleum. These had already been purchased with the intention of using them as a pipe-dip. The way in which any asphaltum, or indeed any other resinous substance, unites with linseed oil is still very obscure, although such compounds have been made for a thousand years, and probably more. We, however, now believe that any mineral oily ingredient, similar to that which gives elasticity and flowing quality to such asphalts as these, does not promote the proper combination with a vegetable drying oil; and although it does not prevent making an enamel which is very good for some things, it probably is still there and is a source of some ultimate weakness. As the event proved, a very good enamel was made; but the author is inclined to think that it was not so good as that used at Allegheny and Cambridge; but the conditions were different in other ways. This pipe was made the subject of study in 1907, when the conduit was thirteen years old, by R. H. Gaines, then, as now, Chief Chemist of the New York City Board of Water Supply. His report was made to the American Electrochemical Society, and discussed at their annual meeting in 1908. He reported that for some years it was thought an ideal coating, but that rusting in small spots had been discovered, at first in low, wet ground in a cedar swamp. Since then many rusting centers have been found, and while the whole of the conduit is still in use (after nearly thirty-seven years) it is often necessary to make local repairs. It was concluded by Gaines, and generally agreed to in the discussion, that the immediate cause was the presence of electrolytes in small, wet patches of surrounding earth, and that in well-drained parts no corrosion took place, and that corrosion on the inside of the pipe was negligible. An electric tension, too small to be easily measured on such a thing as a water main, is known to be adequate, if the current can pass, to produce pitting and eventual perforation. The author coated small steel samples with two coats (twice baked) of such enamel as was used on the Allegheny pipe, which when tested in one of the electrical testing laboratories showed insulation until 6000 volts was reached; but it was suggested that an alternating current, as from an electric rail line, might cause the coated surface to act as a condenser and thus produce a break. It may be that asphaltum of a lower grade, as that used in the Rochester coating, makes a less durable enamel; the author believes this to be one of the causes of trouble. In addition, the better method of coating used at Allegheny probably had much effect. In any case, the fact that this coating, on so large an area, remained apparently uninjured after thirty-six years is perhaps a longer test than is elsewhere on record, and is, at all events, worth knowing.

APPLICATION OF CONTROL ANALYSIS TO THE QUALITY OF VARNISHED CAMBRIC TAPE

By M. F. SKINKER[1]

SYNOPSIS

The purpose of this investigation was to analyze the effectiveness of the present specifications for varnished cambric tape. Statistical analyses were made on the results of specification tests of varnished cambric from three manufacturers. Many shipments were found to have excessive variation. This variation may be due to the method of manufacture or to the method of sampling. As a result of the excessive variation, the user is unable to determine from samples the quality of the shipment of tape.

Under the present purchase specifications for bias-cut varnished cambric tape, most of the tests are necessarily destructive and the report must be made on samples. It is important therefore that the data determined from these samples be representative of the material as a whole. The sampling method used was similar to that usually applied in present-day specifications for material of this character. One roll was taken at random from each group of 500 rolls purchased. On each of these samples, 10 measurements of dielectric strength were made of the material as received. The investigation here reported was on the product of three manufacturers. There are twelve shipments for manufacturer A consisting of a total number of measurements of 1500, manufacturer B five shipments and 500 measurements, and manufacturer C four shipments and 220 measurements. Control analyses were made of these measurements. Some analyses also were made on dielectric strength after other tests such as heating in dry air, in hot oil and after tape had been stretched.

In dividing the data into subgroups for the analysis, the grouping of the ten measurements on each roll was considered. This would be most effective for determining excessive variation from roll to roll. It, however, would give a small number of subgroups and would not give a measure of the variations within the roll. Therefore, subgroups of five were chosen, two subgroups from each roll. The arithmetic mean and the standard deviations for each subgroup were computed. Limits were then established about the arithmetic mean

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[1] Assistant Director of Research, Brooklyn Edison Co., Brooklyn, N. Y.

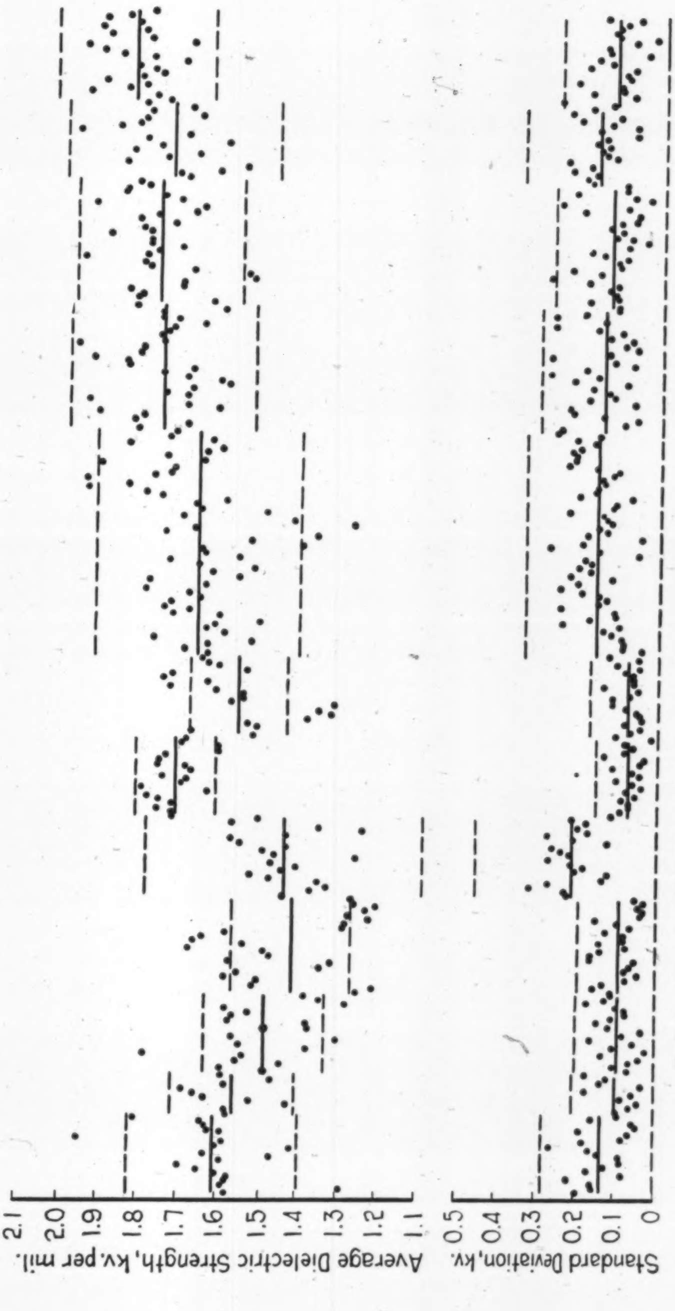

FIG. 1.—Results of Dielectric Strength Tests on Varnished Cambric, Manufacturer A.

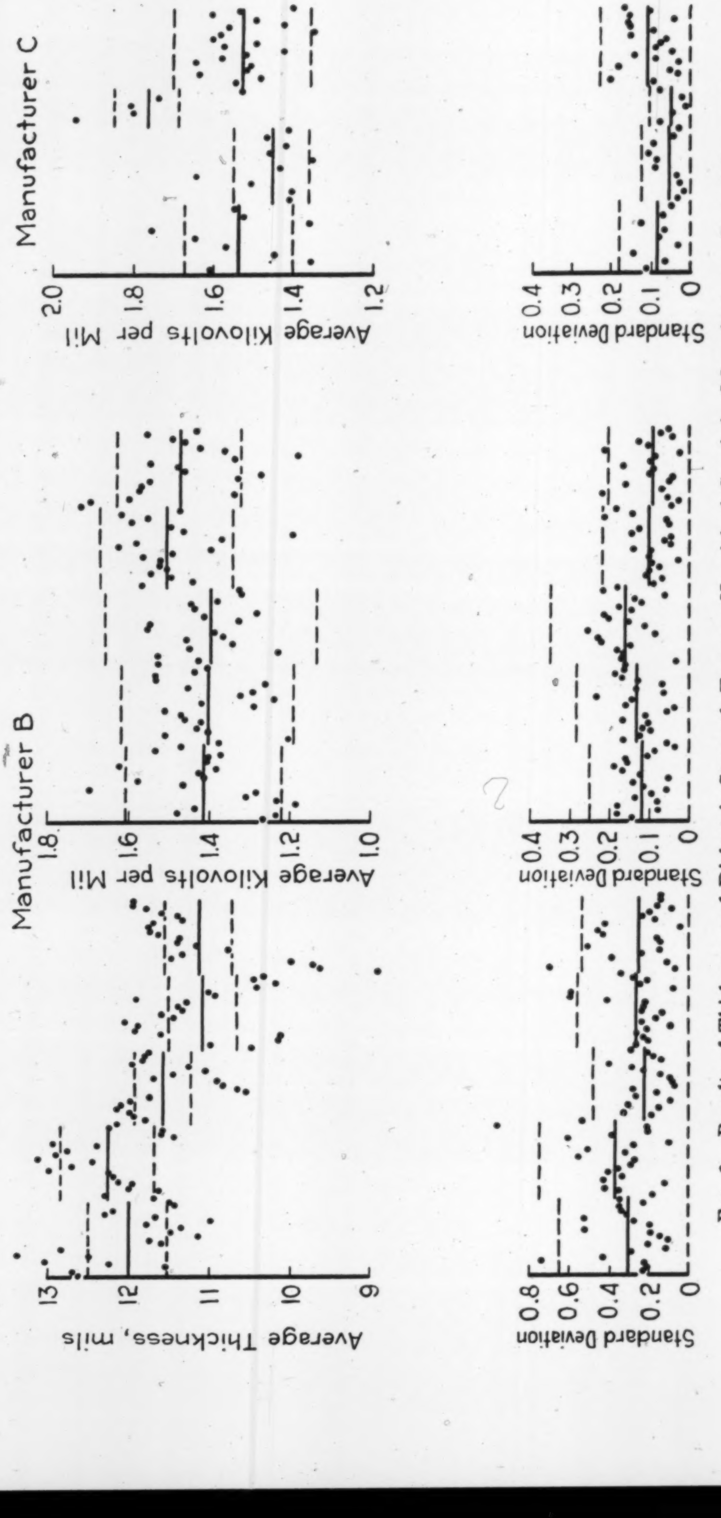

FIG. 2.—Results of Thickness and Dielectric Strength Tests on Varnished Cambric, Manufacturers B and C.

for each of these two statistics. For this investigation, limits about the arithmetic mean of three times the standard deviations have been used. This is Criterion I, as described in W. A. Shewhart's book, "Economic Control of Quality of Manufactured Product." After the limits were established, control charts were plotted, the abscissa being successive samples and the ordinates being their values of kilovolts per mil of thickness. The mean value and limits of three times the standard deviation were also placed on these charts. Separate charts were made for each manufacturer. For each successive shipment, independent limits were used on the control charts because it is not probable that each shipment would be controlled on the same level of quality.

The variation in the average value from shipment to shipment was large. Two-thirds of the shipments that were tested showed excessive variation from roll to roll and there was evidence of excessive variation within the roll. The latter is shown by the two consecutive points from one roll, in Figs. 1 and 2, one sometimes well within the limits and the other outside. Excessive variation from roll to roll may be due to the shipments not being homogeneous in quality or because in the manufacture there is systematic variation. Such systematic variation is likely because of the method of cutting the rolls of varnished cambric tape from the sheet of cloth on which the varnished film was applied. It is quite obvious that unless some compensating means was used, the drying of the varnished film would be more rapid on the edges of the cloth than towards the center, and due to tension there is some variation in thickness of the cloth itself toward the edges.

From this analysis it seems that the sampling method used in our present-day specifications is unsatisfactory. A sample from the mixture of rolls may not give any idea whether or not the material is controlled, and it is obvious that if the samples chosen show a lack of control any deductions from the sample will not give a true indication as to the actual quality of the tape.

A few shipments were analyzed in regard to thickness and total kilovolts of breakdown to see if the lack of control on either of these could be the cause of the variations in the kilovolts per mil of thickness. Excessive variation was found in both.

In order to determine more about tests that are specified in the Society's Tentative Methods of Testing Varnished Cloths, etc. (D 295 – 29 T),[1] the breakdown values after the dry heat, hot oil, and

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 29, Part I, p. 786 (1929); also 1931 Book of A.S.T.M. Tentative Standards, p. 706

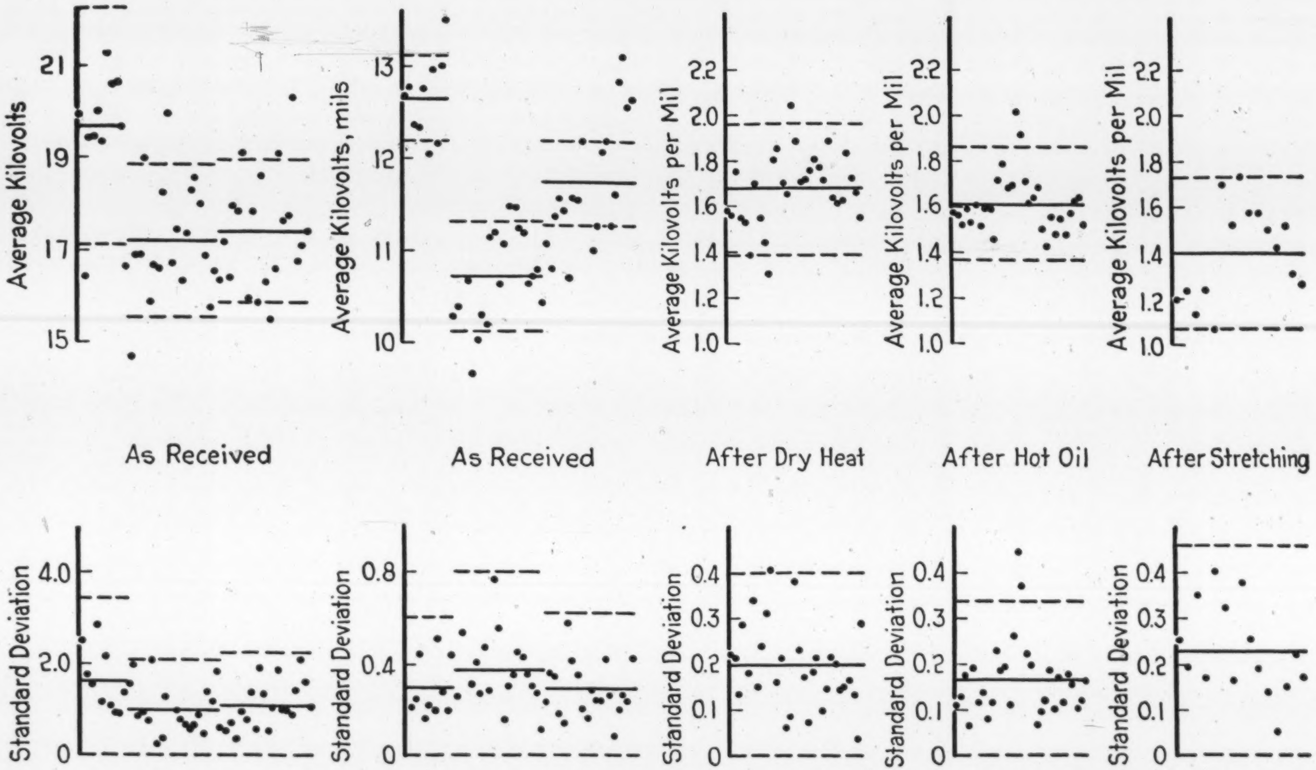

FIG. 3.—Results of Miscellaneous Tests on Varnished Cambric, Manufacturer A.

the stretch test were analyzed. These analyses, Fig. 3, showed variations of the same order. It therefore seemed probable that the tests themselves were satisfactory.

This analysis shows that until we find some better method of making varnished cambric tape, or some better way of sampling tape, or both, it will be impossible for the user to test a few samples and be satisfied that he is getting a good quality product. It is far more important that we get uniformity than it is that we get higher average values. If the material is not controlled we cannot go by probable values, but must use minimum values in our designs; and since the larger the number of samples the smaller the minimum becomes we must therefore use large factors of safety. Some of our present specifications allow 50 to 60 per cent of the rolls tested to fail before the shipment is rejected. This amount of allowable failures is quite ridiculous but the above analysis gives some indication why this is necessary.

It is to be hoped that when the manufacturers are making changes in their product such as improving dielectric breakdown, reducing the power factor or improving dielectric strength after stretch, they will analyze their results by some statistical method so as to determine whether or not they have improved the quality of the product as well as the average value.

THE VOLATILE COMBUSTIBLE MATTER OF COAL-TAR PITCH

By J. M. Weiss[1]

Synopsis

This paper is a study of the factors involved in the determination of volatile matter in coal-tar pitch, by the usual platinum-crucible method used on coal. It is demonstrated that with rapid heating, the initial rush of volatile matter causes entrainment of non-volatile matter and gives results higher than the truth. If slow initial heating is employed to minimize entrainment, cracking takes place so that with very slow heating, results lower than the truth are obtained. The results obtained with any specific set of manipulative details depend largely on the resultant of these factors which work in opposite directions.

The addition of inert non-volatile matter to the sample tested inhibits entrainment and allows more rapid heating. If true volatile contents are required by commercial needs, some method along these lines should be developed. Present methods in use will give check results if the conditions of heating are carefully controlled, but these methods may or may not indicate the true volatile matter of a specific sample. The paper is illustrated with several charts showing graphically the experimental results obtained.

The test for volatile combustile matter is not a usual one in specifications for pitch for domestic use. It is, however, almost invariably a part of specifications for briquet pitch for shipment abroad. For this purpose, an accurate estimation of volatile combustible matter is not the essential factor and all that is really required is a method on which buyer and seller can agree. A general review of the subject and the literature then existing was made by S. R. Church and W. H. Fulweiler.[2]

The author was not in accord with their conclusions and is now in a position to present data which was of necessity confidential at that time.

In the determination of volatile matter in pitches, a 1-g. dry sample is placed in a 20-ml. platinum crucible and exposed to the full heat of a Meeker or Bunsen burner, usually for 7 minutes, the loss in weight constituting volatile combustible matter. It was usual practice in the United States tar industry to use preheating before the 7-minute full-heat period "to prevent foaming" but the exact time or method or preheat was not standardized and variations in the manipulation caused differences in results. If an actual determination of true volatile combustible matter were desired, the operator was between two extremes, first, that preheating caused a certain amount of cracking and carbon formation which decreased the apparent amount of volatile matter, and, second, that the heat if applied full at once caused a very rapid boiling of the oils in the pitch which caused entrainment of the liquid and consequently volatile combustible matter results higher than the truth. This last is vigorously denied by Church and Fulweiler on the basis that they "observed" no "foaming over."

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[1] President, Weiss & Downs, Inc., New York City.

[2] S. R. Church and W. H. Fulweiler, "The Test for Volatile Combustible Matter as Applied to Coal-Tar Pitch," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 848 (1928).

In attacking the problem the author experimented with various periods of preheating and in order to limit the personal equation used a burner in a fixed position and varied the size of the flame to obtain different preheating periods. Usual practice had been to use a full-size flame and wave it over the crucible so as to heat it up at a materially slower rate than if the full flame were applied. The time of preheating was taken from the first visible vapor issuing from the crucible to the time when the bottom of the crucible just showed redness. No appreciable cracking would result until the pitch began to boil and give off vapors, and during the period from this until the bottom of the crucible was red gave approximately the same gamut of temperature during the preheat. A large part of the volatile matter present was expelled during the preheating period as above defined.

The results on two briquet pitches (181 and 189° F., 83 and 87° C.), made from coke-oven tar are shown graphically in Fig. 1. These curves show the same characteristic type of results. With the longer times of preheat, the volatile matter increases as the time decreases as an approximately straight-line function. The points on the straight line, which are averages of two determinations, show in all cases no more deviation than the experimental error of the test. Such a result is to be expected if cracking is the only result, as this is in general a direct function of time with constant temperature. The approximately true volatile matter should be shown by extrapolating the straight line to zero time which has been shown by the dotted line. At somewhere around 1½ minutes preheat, the results deviate rapidly from the straight line as the preheat time decreases. This rapid increase of indicated volatile matter can only be explained

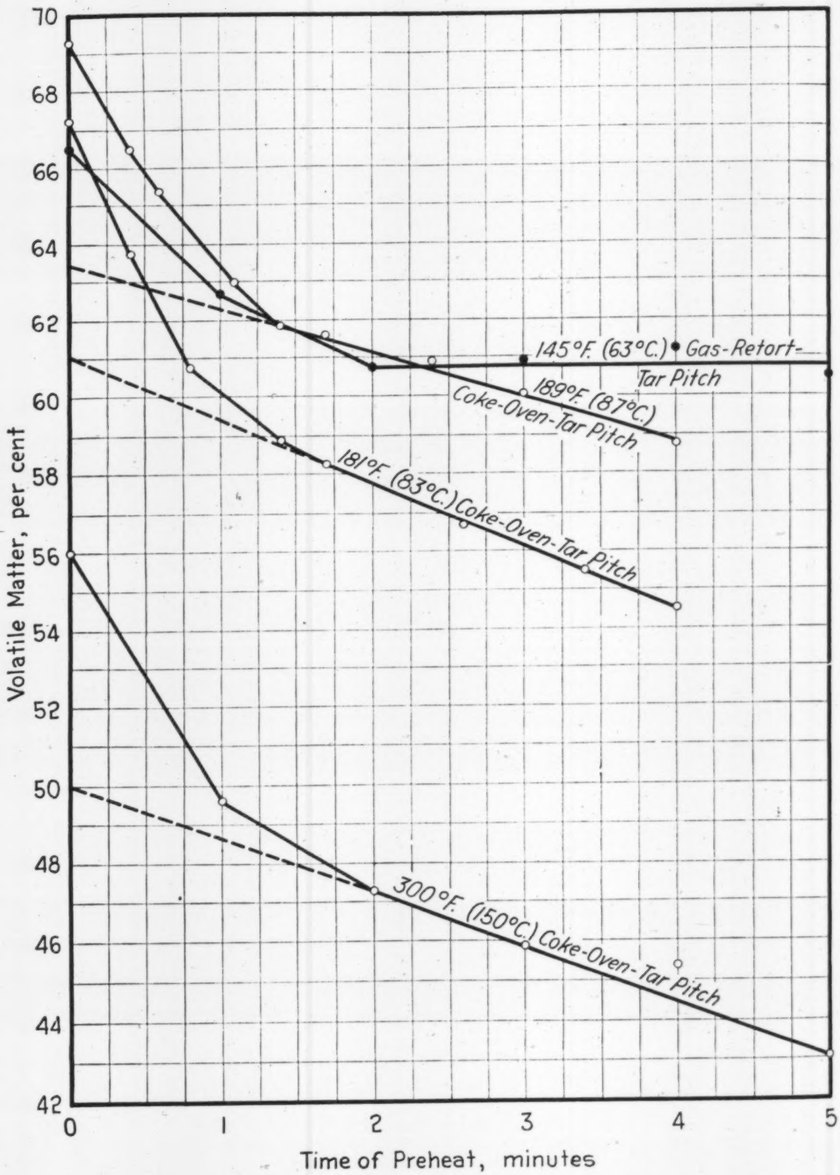

FIG. 1.—Results of Volatile Matter Determinations on Various Types of Pitches.

on the basis of entrainment and consequent loss of matter not truly volatile and is a far more serious source of error than the preheat cracking when the preheat is not an unusually prolonged one.

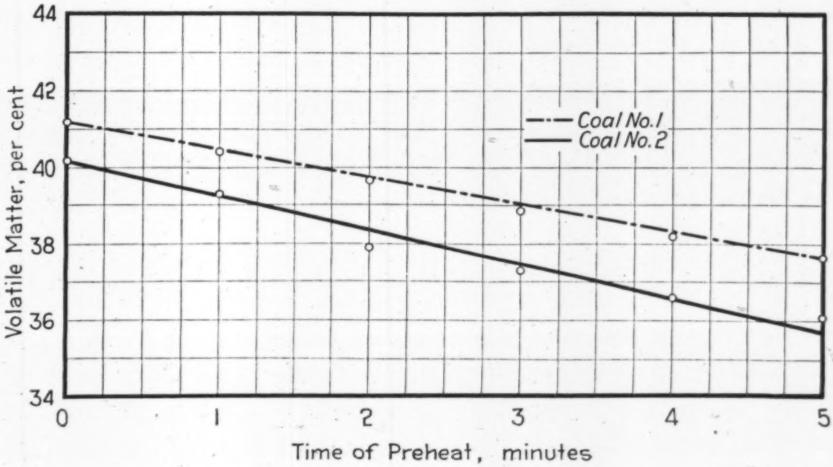

FIG. 2.—Results of Volatile Matter Determinations Using Two Types of Coal.

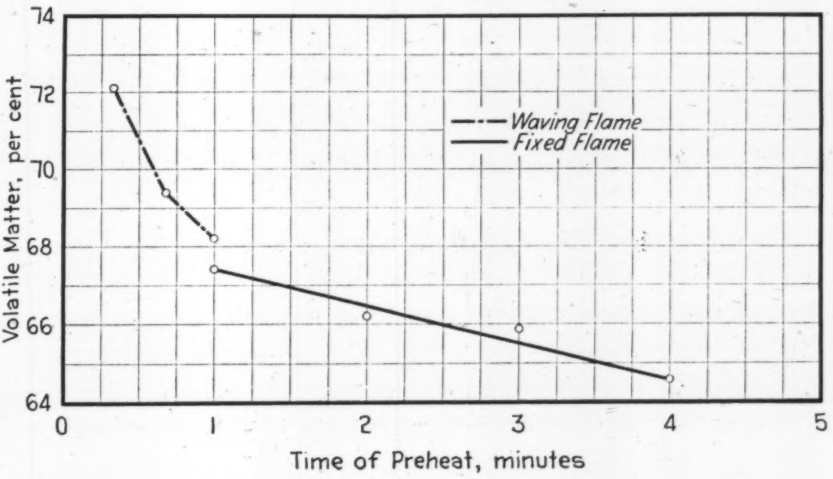

FIG. 3.—Results Obtained from Church and Fulweiler Tests.

Similar results on a higher-melting coke-oven-tar pitch (fuel pitch), give the same type of curve. Results on a high-free-carbon gas-works-tar pitch are also shown in Fig. 1. Gas-works tars during formation are subjected to higher temperatures than coke-oven tars and are therefore less susceptible to thermal effects. In this case error due to cracking during the preheat is negligible, as between two and five minutes the straight line is parallel to the base. The error due to entrainment with rapid heating is of the same order of magnitude as with the coke-oven-tar pitches as evidenced by the deviation when the preheating time falls below two minutes.

As a final test, coal was employed using a Pennsylvania and an Alabama high-volatile coal. In coals we do not have a truly liquid condition conducive to entrainment and the curves in Fig. 2 which are straight lines without a break at low preheat times bear out the explanation of the pitch results. Here cracking is the only effect and the entrainment deviations are absent.

The data given in the paper by Church and Fulweiler also lead to the same conclusion on further analysis. In Table III of their paper, results of varying the time of preheat are shown. Two methods of preheat are used, one with a small fixed flame and the other waving a large flame over the bottom and sides of the crucible. These results are plotted in the accompanying Fig. 3. The similar type of curve to the ones determined by the author are very evident. The waving method with the large flame applied for 20 seconds, which Church and Fulweiler suggest (if any preheating is to be used), actually gives higher volatile matter results than if no preheating at all is employed. This is because all such a preheating does is to melt the pitch before the full flame is applied. Hence, the speed of boiling is faster and more entrainment results.

The results given by Church and Fulweiler in Table IV also negate their conclusions. In a set of results they covered the pitch with silica sand before ignition. The presence of such a large amount of inert matter (ten times the weight of pitch) should inhibit entrainment. The results show that it does since the volatile combustible results are very close to those obtained when preheating was used and far from those where preheating was omitted. These results were so striking that a few tests were run to confirm the conclusion, using a pitch of 191° F. (89° C.) melting point (air bath). Two types of ignited sand were used, one fine (passing No. 40 and retained on No. 60 sieve) and the other coarse (passing No. 20 and retained on No. 30 sieve). Volatile combustible tests were run covering the pitch with 10 g. of sand and applying the flame for the full 7 minutes, without preheating. The following results were obtained:

	Volatile Matter, per cent
No sand	66.3
40 – 60 sand	61.9
20 – 30 sand	61.3

Each result represents the average of two close checks (± 0.1 per cent). A difference of about 5 per cent in volatile combustible matter is produced by the use of sand. It is interesting to note that in the results shown in Fig. 1, the volatile combustible matter with no preheating is from 5.7 to 6.3 per cent higher than the theoretical volatile obtained by projecting the straight-line portion of the curve to zero time.

In conclusion, the author submits that volatile combustible tests on pitch either by the A.S.T.M. coal method or by the British method using a crucible with a hole in the lid will give check results between different operators using no preheating. If, however, the test is supposed to show the volatile matter obtained in use, it is decidedly faulty and inaccurate. If an accurate test is desired, it will be necessary to standardize the preheating time and method of preheating so as to place both cracking and entrainment at the minimum where they will approximately counterbalance each other. Alternately the use of an inert addition to minimize entrainment when no preheating is used may prove to be a more convenient solution. Preliminary results indicate that this last method will prove to be a satisfactory solution of the problem.

DISCUSSION

Mr. A. C. Fieldner[1] (*presented in written form*).—At my request, Mr. H. M. Cooper, chemist-in-charge of the coal analysis laboratory of the U. S. Bureau of Mines at Pittsburgh, Pa., determined volatile matter in samples of hard and soft pitch according to the method described by Mr. Weiss in his paper, and also by the so-called modified method used by the Bureau for coals which throw off sparks such as lignite and sub-bituminous coal. This method involves preheating similar to that used on pitch. The results are given in the accompanying Table I and Figs. 1 and 2.

Table I.—Results of Volatile Matter Determinations on Coal-Tar Pitch.

Volatile matter values are given in per cent.

Meker Burner[a]							Electric Furnace[b]					
Method A	Method I	Method C	Method D	Method E	Method F	Method G	Method A	Method H	Method M	Method J	Method K	Method L
Sample No. 17-2												
59.71	56.55	56.05	52.14	49.69	48.74	47.72	58.69	52.75[c]	71.04[d]	.....	50.13[c]	47.80
59.81	56.63	55.95	52.39	49.66	48.35	47.88	58.66	53.30[c]	78.88	75.09[d]	51.49	48.26
.....	.....	.....	.....	.....	48.35	47.75	58.73	.....	.....	.....	.....	48.46
59.76	56.59	56.00	52.27	49.68	48.48	47.78	58.69	53.03	.....	75.09	50.81	48.18
Sample No. 19-5												
90.86	89.74	88.55	87.39	86.75	85.40	84.30	90.25	90.88[c]	91.69[d]	90.73[c]	88.52	84.89
90.71	.....	88.77	.....	.....	.....	.....	90.09	.....	.....	.....	.....	84.87
90.94	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
90.84	89.74	88.66	87.39	86.75	85.40	84.30	90.17	90.88	91.69	90.73	88.52	84.88

[a] *Method A.*—7 minutes at 950° C. (1740° F.).
Method I.—½ minute preheat followed by 7 minutes at 950° C. (1740° F.).
Method C.—1 minute preheat followed by 7 minutes at 950° C. (1740° F.).
Method D.—2 minutes preheat followed by 7 minutes at 950° C. (1740° F.).
Method E.—3 minutes preheat followed by 7 minutes at 950° C. (1740° F.).
Method F.—4 minutes preheat followed by 7 minutes at 950° C. (1740° F.).
Method G.—5 minutes preheat followed by 7 minutes at 950° C. (1740° F.).

[b] *Method A.*—7 minutes at 950° C. (1740° F.).
Method H.—7 minutes at 640° C. (1185° F.) followed by 5 minutes at 950° C. (1740° F.).
Method M.—7 minutes at 725° C. (1335° F.) followed by 5 minutes at 950° C. (1740° F.).
Method J.—7 minutes at 800° C. (1470° F.) followed by 5 minutes at 950° C. (1740° F.).
Method K.—5 minutes gradual heating followed by 5 minutes at 950° C. (1740° F.).
Method L.—(Standard coal modified method as used for lignite)—7 minutes gradual heating followed by 5 minutes at 950° C. (1740° F.).

[c] Slight foaming. [d] Copious foaming.

Two pitches were used, designated Nos. 19-5 and 17-2. The first, No. 19-5, was a soft somewhat gummy pitch, resulting from a

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[1] Chief Engineer, Experiment Stations Division, U. S. Bureau of Mines, Washington, D. C.

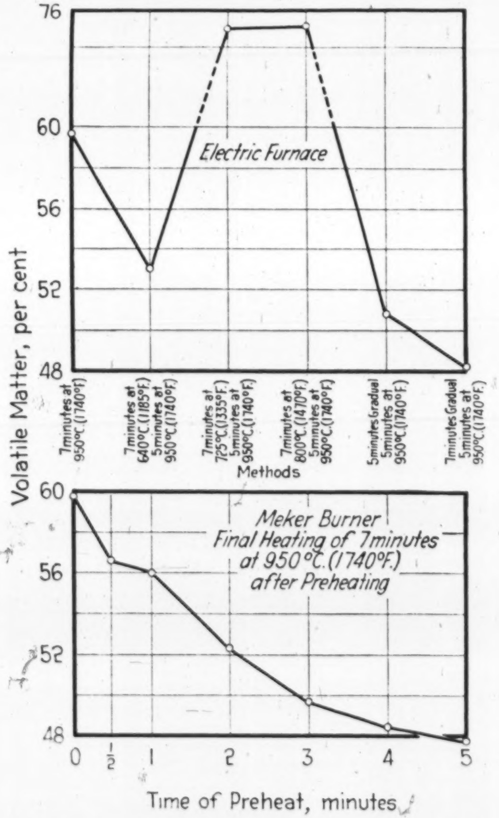

FIG. 1.—Results Obtained on No. 17-2 Coal-Tar Pitch Using Electric-Furnace and Meker Burner.

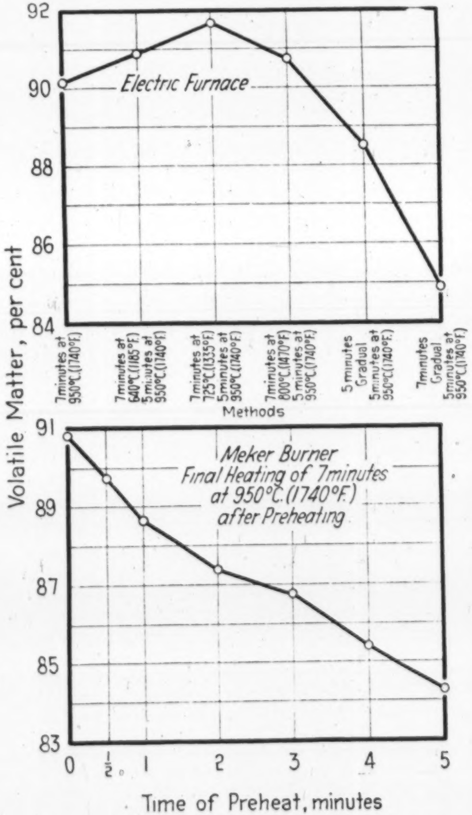

FIG. 2.—Results Obtained on No. 19-5 Coal-Tar Pitch Using Electric-Furnace and Meker Burner.

cut at 350° C. (660° F.) in distillation of a tar obtained by carbonization of coal at 500° C. (930° F.). The second, No. 17-2, was a hard brittle pitch, cut at 350° C. (660° F.) in the distillation of a tar obtained by carbonization of coal at 1000° C. (1830° F.). It was broken down to pass a No. 28 sieve, from which the samples were taken. The soft pitch had to be cut out in lumps for the determinations.

A No. 3 Meker type burner and a vertical electric volatile-furnace were used for the tests. The temperatures of the crucible, both in the flame and furnace, were checked with a thermocouple to control the temperature of the final heating. A 10-ml. platinum crucible with capsule cover was used.

Methods of preheating in the Meker burner method were as follows:

Method A.—7 minutes at 950° C. (1740° F.).
Method I.—½ minute preheat followed by 7 minutes at 950° C. (1740° F.).
Method C.—1 minute preheat followed by 7 minutes at 950° C. (1740° F.).
Method D.—2 minutes preheat followed by 7 minutes at 950° C. (1740° F.).
Method E.—3 minutes preheat followed by 7 minutes at 950° C. (1740° F.).
Method F.—4 minutes preheat followed by 7 minutes at 950° C. (1740° F.).
Method G.—5 minutes preheat followed by 7 minutes at 950° C. (1740° F.).

The burner preheating period was timed as recommended by Weiss, that is, ". . . . the time required for preheating was taken from the first visible vapor issuing around the crucible lid to the time when the bottom of the crucible just showed redness . . ."

Using the vertical type electric furnace, which is standard for coal analysis, the methods employed were as follows:

Method A.—7 minutes at 950° C. (1740° F.).
Method H.—7 minutes at 640° C. (1185° F.) followed by 5 minutes at 950° C. (1740° F.).
Method M.—7 minutes at 725° C. (1335° F.) followed by 5 minutes at 950° C. 1740° F.).
Method J.—7 minutes at 800° C. (1470° F.) followed by 5 minutes at 950° C. (1740° F.).
Method K.—5 minutes gradual heating followed by 5 minutes at 950° C. (1740° F.).
Method L.—(Standard coal modified method as used for lignite) – 7 minutes gradual heating followed by 5 minutes at 950° C. (1740° F.).

Foaming did not appear in any of the burner determinations, but did in some of the preheating periods in the electric furnace. Where the foaming occurred, it was quite vigorous. Due to smoke, it was impossible to see the crucible during the regular 7 minute heating at 950° C. (1740° F.) in the electric furnace, but the appearance of the crucible after the determination indicated no foaming, as it was clean of deposits. The crucible, where foaming was noted, had considerable deposit of carbon on the outside which had not burned away.

Mr. Cooper's results did not fall in a straight line. The line joining the points has more slope than most of the curves shown in the paper; and it would be difficult to extrapolate to zero preheat and obtain any great difference between the direct determination without preheat, and the extrapolated result. From these two tests, I would hesitate to put any great dependence on the point of intersection of the extrapolated line with the zero axis, especially if done in different laboratories by different chemists, but I take it that Mr. Weiss does not mean to propose this extrapolation method for routine determinations, but rather to bring out variations inherent in the method of determination.

It is interesting to note that the results obtained by direct heating for seven minutes without preheat check closely; also the result obtained by seven minutes heating with the Meker burner checked those obtained with the electric furnace without preheat in both cases. If there were any loss by entrainment it was the same in both methods. Good agreement in results was not obtained using the electric furnace and the Meker burner with preheating, until after the preheating period exceeded four or five minutes. Seven minutes preheating with the electric furnace and five minutes with the Meker burner gave good agreement between the two types of apparatus.

MR. S. R. CHURCH.[1]—Mr. Weiss has rightly stated that from a practical standpoint it does not matter what variation of the volatile combustible method is adopted provided buyer and seller are in agreement as to the details of the test. Experience has shown that very good check results can be obtained when preheat is used or when it is not used.

Like most of our tar testing methods this is an empirical test, so also is our test for free carbon in tar or pitch which does not actually give free carbon in the exact meaning of the words, nor does our melting point method give the true melting point. The volatile test on pitch is generally of interest only when the pitch is to be used for making fuel briquets. The consumption of pitch for this purpose is almost entirely in Europe; we export this pitch on specifications drawn in Europe. On the Continent and in Great Britain they have generally adopted specification requirements for the volatile test which do not include a preheating requirement. The method in most general use at present has been published by the Committee on Standardization of Methods for Testing Tar Products (London). It is similar to the American standard coal method except that the lid of the crucible has a hole on the center to facilitate the escape of flame.

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[1] Consulting Chemist, New York City.

I do not agree with Mr. Weiss' theory that there is unburned material carried over or lost during the heating period, which is the basis for his criticism of a previous paper by Mr. Fulweiler and myself.

MR. H. C. PORTER[1] (*presented in written form*).—This paper illustrates the important principle that methods of test frequently cannot be standardized on any other basis than one of strict adherence to manipulative detail. There is no "true volatile content" of such a material as pitch, although the author of this paper has used that expression repeatedly. The volatile content is not present as such but is formed by the conditions of heating. In order to establish any standard for this determination, it is necessary merely to choose a procedure which can best be duplicated in the hands of different manipulators and on different grades of material so as to introduce the least possible error.

As the author has stated, it is probably true that a lesser amount of manipulative error will be introduced if the pitch be given a certain amount of preheat at a moderate temperature so as to avoid entrainment of liquid particles. This will not do away with cracking, however, since the products driven off from pitch at temperatures above 300° C. (570° F.) are very easily decomposed and a distillation without decomposition is probably impossible unless under vacuum. It is therefore necessary, as the author brings out, to balance as nearly as possible, in the method chosen, the errors due to entrainment and those due to cracking so that different manipulators can have the best chance of duplicating results.

It is difficult to understand just what the author means by the volatile matter actually obtained in practice, that is in the use of a fuel pitch. This, of course, would vary between wide extremes according to the way in which the briquets or other fuel containing the pitch were burned in practice.

In his reference to results of Church and Fulweiler in experiments using a large amount of sand in the crucible, the author does not make reference to the possibility of a considerable amount of cracking in this case by passage of the volatile products through the heated sand. Such cracking would undoubtedly occur and would explain the lower results on volatile matter obtained with the sand. It is probably true that the avoidance of entrainment in this case has also something to do with the lower result. Cracking in any case is greatest with quick, high heating, and not at its lowest, as the author seems to imply. If such a test is to be standardized on fuel pitch, it is advisable merely to choose a method of manipulation which will minimize the chances for irregular errors in the hands of different manipulators and for losses by decrepitation which do not truly represent the index or characteristic that it is desired to establish. In the standard method for determination of volatile matter in coal such a contingency is provided for by a modification to be used with coal or similar materials that decrepitate by rapid heating.

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[1] Chemical Engineer and Chemist, Philadelphia, Pa.

MR. CHURCH.—May I comment on Mr. Porter's statement? It seems to me quite extraordinary that we get very concordant results with the British method, where there is a definite hole 2 mm. in diameter in a crucible lid, and the American coal method with a tightly fitting inverted lid, if there is a tendency for a large amount of decrepitation, entrainment or sparking. The popping and sparking of these semibituminous coals is an entirely different phenomenon from what happens when you put pitch in the crucible, because it immediately melts and becomes liquid and cannot pop.

MR. PORTER.—In that condition it decomposes very rapidly and drives off large quantities of gas and other products in a rush, and any phenomenon like that carrying off large volumes of gas and vapors quickly from a small body of liquid is likely to entrain and carry off particles of the liquid. I have never been able to check as well by the rapid heating method as I have by the modified preheating method.

MR. J. M. WEISS.[1]—I am able to check on a seven minute period with any method of heating as long as the conditions are kept constant, or with any method of preheating, and I agree with Mr. Church that it is easier to keep constant with no preheating than with preheating. I am not trying to be an advocate for one method or another, I am simply trying to bring out some of the basic facts underlying the volatile determinations when applied to pitch, so that we shall be able to evaluate the effect of preheating and entrainment. We shall then have some method of attack which enables us to make an approach to problems which may arise.

MR. C. S. REEVE.[2]—I think Mr. Fieldner's results are quite interesting, showing the possible greater variation in the trend of those curves as a result of preheating by what are supposed to be identical methods. The effect of preheating and cracking is a function of time and temperature, and the condition of preheating as Mr. Weiss has brought out is a very difficult thing to control and standardize. Mr. Fieldner's results compared with those of Mr. Weiss bring that out.

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[1] President, Weiss & Downs, Inc., New York City.

[2] Manager, Research Development, The Barrett Co., New York City.

For that reason, several years ago we discontinued the preheating method on tars and pitches, and the possibilities of checking among ourselves or between producer and consumer are much better by the seven minute method than they are by even any closely described method of preheating. One cannot describe that heating exactly. What we need is a method of dealing with the consumer, principally, and there is no difficulty in getting checks by the seven minute method, whether there is entrainment or no entrainment, and therefore we are using that method.

MR. WEISS.—I fully agree with Mr. Reeve's stand on this matter; I think from a commercial standpoint, dealing with a particular class of pitches, that the method he is using is fully satisfactory. However, what I want to bring out is that if you try to take two entirely different classes of pitch, one of 90 per cent volatile matter and another of 15, 20 or 30 per cent, the two are not comparable, and when we are trying to draw conclusions, we must recognize that the test is entirely empirical. We do not, for example, want to attempt to draw comparisons between pitch and asphalt by volatile matter tests. The thing may not have the same meaning; the more volatile matter you have, the more entrainment of solids you have, and you do not see this loss flowing over the top of the crucible. We cannot take a volatile matter determination by present methods and compare two materials of entirely different natures and have the comparison mean anything. A method to have any theoretical significance, must take all factors into consideration.

(*Author's closure by letter*).—The results presented by Mr. Fieldner are quite interesting. The differences in results obtained are certainly due to variations in preheat method between his laboratory and ours. Our preheat was carried on with a Tyrell burner where the height of the flame could be varied for the different preheat times desired while his preheat was with a Meker burner which would probably have to be regulated in a different way. It is, however, futile to speculate at length as the real cause of the difference could only be discovered by cooperative work between operators. The personal factor in such preheat tests is large and all details must be standardized if check results between different laboratories are to be obtained.

AN APPARATUS AND METHOD FOR MEASURING THE CONSISTENCY OF ROOFING PUTTIES AND FIBROUS ROOF COATINGS

By G. W. Clarvoe[1]

Synopsis

This paper describes an apparatus and method of test which have been developed for measuring the working consistency of roofing putties and fibrous roof coatings and which have been successfully used in the laboratories of the author's company for a period of over one year. The apparatus is based upon the principles of the falling ball and falling cylinder viscosimeters, the falling ball principle being applied to the measurement of materials of brushing consistency and the falling cylinder to putties and extremely viscous liquids.

Data are presented to show the sensitivity of the apparatus, its reliability, and its applicability for use with the materials in question. Consistency differences produced by the addition of small quantities of fiber or solvent to roofing putties or fibrous roof coatings are shown to be readily measurable. A close correlation is shown between the measured consistencies and the observations made on practical applications.

Data are given showing the consistency differences found between ten roofing putties of different manufacture and indicating the need for standardization of this and similar products. Tentative specifications for the consistency of roofing putties and fibrous roof coatings are suggested.

The applicability of the apparatus to the measurement of the consistency of a variety of miscellaneous materials is indicated.

Introduction

Consistency is a term which is broadly used and may have many definitions. At various times it is used with reference to degrees of plasticity, viscosity, or the correlated properties. It is used here in the sense of working consistency, or, as it is called with respect to concrete, "workability." It is the resistance to placement of the material by trowelling, brushing, or flow as the case may be. This resistance to working or placement may, in certain materials, be a function of the viscosity, or plasticity, or it may be affected by the oiliness or fiber structure of the material. As we speak of it here our concern is only with the net results of these properties as they affect placement of the material—the working consistency.

A roofing putty or fibrous roof coating is generally a mixture of asphalt or coal tar, mineral matter usually containing some fibrous material such as asbestos, and a solvent. As the fiber and filler content increase, the mixture decreases in mobility and its plastic yield value is increased. With no filler or fiber, the mixture would generally behave as a viscous material. With an appreciable quantity of fibrous material present, the plastic yield point is obscured, and once the yield point is reached the mixture does not behave as a viscous material because of the structural interlacing and stiffening of the fibrous material. An apparatus which will successfully indicate consistency must be susceptible to viscosity and plasticity variations, must measure the matting or stiffening due to fibrous material, and, in spite of this matting, must operate satisfactorily.

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[1] Asphalt Chemist, Research Laboratory, Johns-Manville Corp., Manville, N. J.

Heretofore, the consistency of a putty or roof coating has been largely dependent upon the judgment of the plant operator. Changes in personnel resulted in changes in the consistency of the product, while with the same operator, air temperature changes produced quite different opinions as to the correct consistency. Inasmuch as the variations which occur in the raw materials used in the manufacture of these products do not permit the strict adherence to definite formulas, the formulas could not be used as bases for the manufacture of similar products at all times. In most cases the plant operator worked towards uniform consistency, as judged by hand working, and varied the formula slightly to produce a product which conformed to his ideas of the desired material.

The need for standardization of these products on a consistency basis is obvious. Manufacturers of roof coatings and putties with plants located in different parts of the country find it expedient to use raw materials available locally with the result that considerable trouble is frequently encountered in marketing a uniform product which, in the hands of a given consumer, would be considered to have the same consistency regardless of the location of the manufacturing plant. Likewise, the standardization of the products of different manufacturers on a consistency basis, regardless of composition, would be equally desirable. With the industry standardized, a consumer could, for example, purchase a 10-second putty or roof coating and know definitely that it would meet his particular requirements as to its applicability. When a more easily workable or a stiffer product was found desirable it could be easily specified in definite terms.

The apparatus described in this paper is believed satisfactorily to indicate consistency of these products as judged by the men in the field during application, manufacturing operators, and technical men experienced in their use. The device has been in continuous use for a period of over one year in the laboratories of the author's company with exceptionally satisfactory results. It has given every indication of being reliable, sensitive, and of giving results indicative of application behavior. The machine itself is rugged, easy to operate and permits rapid testing. The sample is quickly prepared for testing and the apparatus easily cleaned.

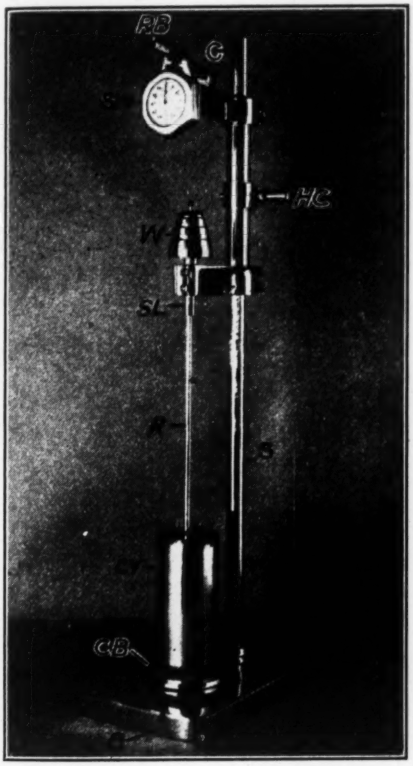

FIG. 1.—Consistometer for Measuring the Consistency of Roofing Putties.

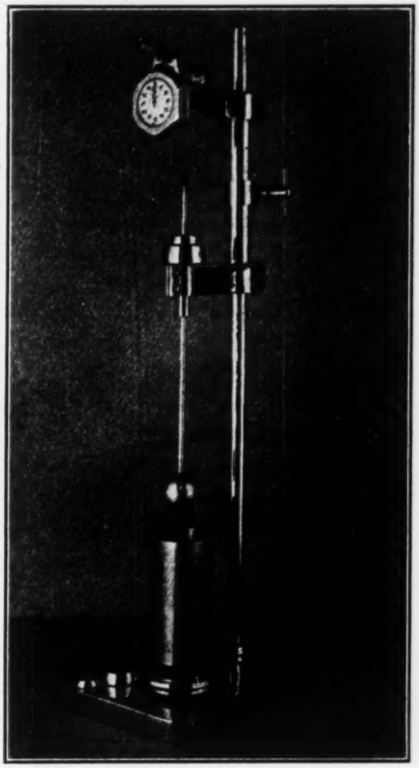

FIG. 2.—Consistometer for Measuring the Consistency of Fibrous Roof Coatings.

Previous to the development of the apparatus described, tests were made using standard plasticity, viscosity, and consistency apparatus commercially available. The devices tested and the reasons for their rejection are given below:

Emley Plasticimeter.—Too low plasticity of materials being tested and their tendency to flow. Not suitable for fluid putties or liquids. High loss of volatile constituents during test. Results not comparable with hand trowelling.

Grease Cone Penetrometer.—Not satisfactory for materials of low plasticity and liquids. Not sensitive to small changes in consistency.

Stormer Viscosimeter.—Not suitable for heavy putties. Erratic results due to fibers.

Orifice Viscosimeter.—Erratic results with materials containing fibers.

Numerous other consistency measuring devices were rejected without trial because of complexity, fragility, and the great length of time required to make the test.

APPARATUS AND TEST METHODS

The apparatus is shown in Figs. 1 and 2. In Fig. 1 is shown the assembly for testing putties, very viscous coatings, and thick liquids. In Fig. 2 is shown the assembly for testing liquid materials such as fibrous roof coatings, paints, lacquers, and bodied oils. The set-up shown in Fig. 1 is based upon the principle of the falling cylinder viscosimeter. A device similar in principle is described by W. F. Busse and W. B. Doggett for use in the measurement of the viscosity of rubber cements.[1] It is also somewhat similar in design to the apparatus described by George A. Smith for measuring the workability of concrete.[2]

The time required for the rod *R* to fall a distance of 4 in. through the medium being tested is recorded as the consistency. This rod is $\frac{1}{4}$ in. in diameter, weighs 75 g., and has a hemispherical end. The upper end of the rod is notched to catch in the mechanism at *C* and is released by pushing the button *RB*. The upper end of the rod carries interchangeable weights giving a load range of from 75 to 500 g. The rod falls through a guide sleeve *SL* which is 2 in. long and with a bore just large enough to allow the $\frac{1}{4}$-in. rod to pass freely. The cylinder *CY* is 5 in. in inside length and 2 in. in internal diameter. It has a screw base *CB*, which is removable for cleaning, and a slip-cap cover. The slip cover is used to prevent evaporation of the solvent while the sample is being brought to temperature in a constant-temperature bath. The base of the cylinder fits into a depression in the base *B* and assists in centering. A stop watch *SW* is an integral part of the device and is automatically put in operation on release of the plunger. The stop watch, release mechanism, and sleeve supports are assembled as a unit which is vertically movable on the stand *S* and may be locked in any position with the clamp *HC*. A pin through the rod supports the weights and governs the distance of fall of the rod.

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[1] W. F. Busse and W. B. Doggett, "Application of the Falling Cylinder to the Measurement of the Viscosity of Thick Rubber Cements," *Industrial and Engineering Chemistry*, Analytical Edition, Vol. 2, No. 3, July 15, 1930.

[2] George A. Smith, "The Measurement of Workability of Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. 28 Part II, p. 505 (1928).

The test is performed as follows: With the rod in the "catch" position the supporting unit is lowered until the tip of the rod just touches the surface of the material under test. The rod is released and timed through a fall of 4 in. The average of five such tests is taken as the consistency.

The device shown in Fig. 2 is similar to that of Fig. 1 except that the $\frac{1}{4}$-in. rod has been replaced by a $\frac{1}{4}$-in. aluminum tube ended with a hollow aluminum ball $1\frac{1}{2}$ in. in diameter. The total weight of the rod and ball is 50 g. The distance of fall is 3 in. rather than 4 in. as on the previous device. The test in this case is made by lowering the support unit with the ball and rod in the raised position until the ball is just covered with liquid. The ball is then released and timed through a fall of 3 in. The average of five tests is taken as the consistency of the sample.

In preparing the sample for test, one or more cylinders are filled by working the material to the bottom with a knife or spatula. Care is taken to see that air is not entrapped when filling. With some putties, difficulty may be encountered in this respect but by prodding with a spatula most of the air bubbles may be broken and the cylinder completely filled with putty. The cylinder is filled to the top edge, leveled off, and capped. In the case of roof coatings no difficulty whatever should be experienced in filling the cylinders. In this case the cylinder is filled to within $\frac{3}{4}$ in. of the top to allow for the ball displacement. The samples thus prepared are placed in a constant-temperature bath at 77° F. (25° C.) and allowed to remain for one hour. In certain cases, depending upon the original temperature of the putty, this time may be considerably shortened.

TEST DATA

Comparison of Consistometer and Hand-Trowelling Results on Putties:

In order to determine whether the consistometer was actually indicating changes in consistency which were readily distinguishable under practical trowelling tests, a series of asphalt roofing putties was made with varying consistencies running from impractically thin materials to those impractically stiff. These were made by using the same base for each sample, adding varying quantities of fiber to produce the desired stiffness. The complete set of putties was then examined by a committee consisting of manufacturing men, field engineers, laboratory men and men experienced in practical applications. The

TABLE I.—COMPARISON OF CONSISTOMETER AND HAND-TROWELLING RESULTS ON ROOFING PUTTIES.

SAMPLE	CONSISTOMETER RESULTS				COMMENTS ON TROWELLING
	LOAD, 75 G.	LOAD, 100 G.	LOAD, 150 G.	LOAD, 200 G.	
No. 1	6.0 sec.	2.5 sec.	too soft	......	too fluid
No. 2	7.5 sec.	4.5 sec.	too soft	......	too fluid
No. 3	too stiff	10.0 sec.	2.5 sec.	1.0 sec.	soft limit
No. 4	too stiff	16.0 sec.	3.5 sec.	2.0 sec.	satisfactory
No. 5	too stiff	14.0 sec.	4.0 sec.	2.0 sec.	satisfactory
No. 6	too stiff	22.0 sec.	5.0 sec.	2.5 sec.	satisfactory
No. 7	too stiff	32.0 sec.	7.5 sec.	3.5 sec.	satisfactory
No. 8	too stiff	24.0 sec.	9.5 sec.	5.0 sec.	satisfactory, slightly stiff
No. 9	too stiff	40.0 sec.	10.0 sec.	4.0 sec.	satisfactory, slightly stiff
No. 10	too stiff	39.0 sec.	12.0 sec.	4.5 sec.	too stiff
No. 11	too stiff	too stiff	26.0 sec.	10.5 sec.	too stiff
No. 12	too stiff	too stiff	31.0 sec.	11.0 sec.	too stiff
No. 13	too stiff	too stiff	too stiff	25.0 sec.	too stiff

NOTE.—Satisfactory range approximately 2 to 10 seconds for 150-g. load. Each result is the average of five tests. Temperature of samples during test, 77° F. (25° C.).

TABLE II.—COMPARISON OF CONSISTOMETER AND HAND-BRUSHING RESULTS ON FIBROUS ROOF COATINGS.

SAMPLE	CONSISTOMETER RESULTS				COMMENTS ON BRUSHING
	LOAD, 75 G.	LOAD, 100 G.	LOAD, 150 G.	LOAD, 200 G.	
No. 1	2 sec.	too soft	......	......	too fluid
No. 2	3 sec.	1.5 sec.	too soft	......	too fluid
No. 3	5.5 sec.	2.3 sec.	1.5 sec.	too soft	satisfactory, slightly fluid
No. 4	9.1 sec.	3.2 sec.	1.2 sec.	0.8 sec.	too fluid
No. 5	9.0 sec.	4.0 sec.	1.5 sec.	too soft	too fluid
No. 6	7.0 sec.	4.0 sec.	2.0 sec.	1.0 sec.	satisfactory
No. 7	13.0 sec.	6.0 sec.	2.0 sec.	1.0 sec.	satisfactory
No. 8	9.0 sec.	4.5 sec.	2.0 sec.	1.2 sec.	satisfactory
No. 9	7.0 sec.	4.0 sec.	2.0 sec.	1.0 sec.	satisfactory
No. 10	9.0 sec.	4.5 sec.	2.0 sec.	too soft	satisfactory
No. 11	12.5 sec.	5.2 sec.	2.2 sec.	1.2 sec.	satisfactory
No. 12	too stiff	11.0 sec.	3.2 sec.	1.5 sec.	satisfactory
No. 13	17.0 sec.	8.5 sec.	3.8 sec.	2.2 sec.	satisfactory
No. 14	17.0 sec.	8.5 sec.	3.8 sec.	2.2 sec.	satisfactory
No. 15	18.0 sec.	9.0 sec.	3.8 sec.	2.0 sec.	satisfactory
No. 16	too stiff	48.0 sec.	9.7 sec.	4.6 sec.	satisfactory, slightly stiff
No. 17	too stiff	38.0 sec.	13.0 sec.	7.0 sec.	too stiff
No. 18	too stiff	too stiff	14.0 sec.	4.5 sec.	too stiff
No. 19	too stiff	36 sec.	14.0 sec.	8.0 sec.	too stiff
No. 20	too stiff	too stiff	34.5 sec.	14.1 sec.	too stiff

NOTE.—Satisfactory range approximately 2 to 10 seconds for 150-g. load. Each result is the average of five tests. Temperature of samples during test, 77° F. (25° C.).

putties were subjected to stirring and trowelling similar to the treatment given in actual use. In all cases the individual opinions were essentially the same, and the consensus of opinion was adopted as the trowelling consistency of each putty. The consistencies of the putties were then measured on the consistometer and in every case the results were in agreement with the opinions of the committee. In several cases the consistometer indicated differences in consistency which were not detected in the trowelling tests but which were believed to exist from knowledge of their compositions. Results of these tests are given in Table I. Tests were performed with the apparatus shown in Fig. 1.

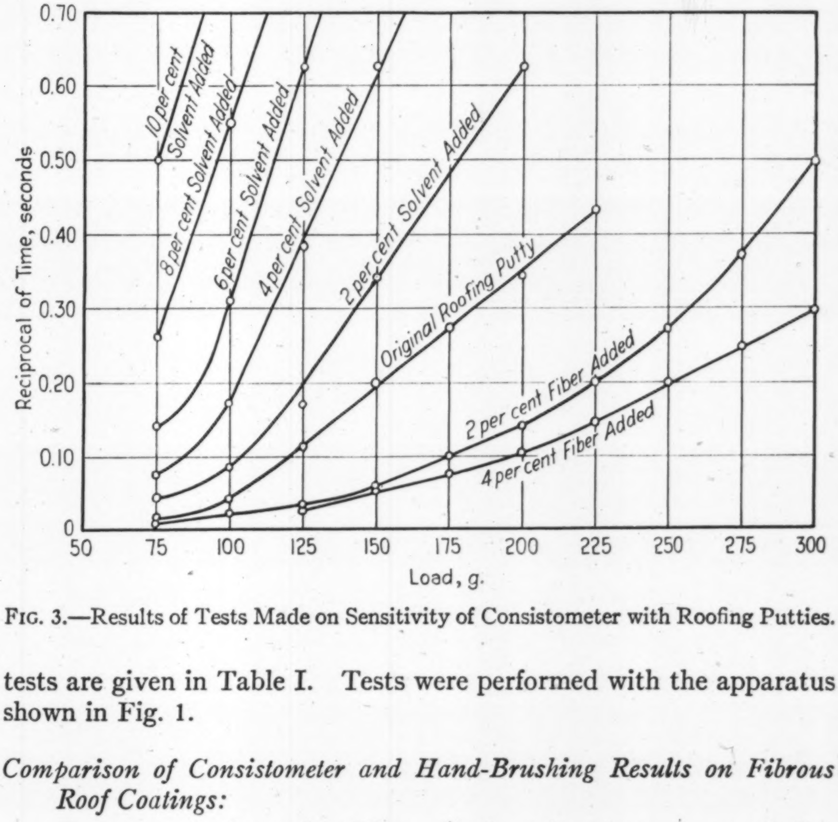

FIG. 3.—Results of Tests Made on Sensitivity of Consistometer with Roofing Putties.

Comparison of Consistometer and Hand-Brushing Results on Fibrous Roof Coatings:

Tests were performed on fibrous roof coatings in a manner similar to those on putties with the exception that the ball device as shown in Fig. 2 was used and the coatings were examined for their brushing properties on prepared roofing and metal. As in the case of the putties, agreement was very close between the opinions of the committee and the consistometer results. Results are shown in Table II.

Sensitivity of Consistometer with Roofing Putties:

In order to determine the sensitivity of the device as shown in Fig. 1 when used on roofing putties, a standard black roofing putty composed of asphalt, asbestos fiber, and solvent was taken as a base and varying percentages of solvent and fiber were added to different samples. Consistency measurements were made on these samples with all possible loads. The results indicate that the instrument is sensitive to solvent or fiber additions of less than 2 per cent. The results are shown in Fig. 3. Practically no variation was obtained on individual tests on the same sample when the average was less than 10 seconds. With averages greater than 10 seconds but less than 20 seconds, the individual test variation was not greater than 2 seconds. From 20 to 50 seconds the maximum variation was 5 seconds. In order to obtain the best results it was found advisable to adjust the weights so that readings would fall between 2 and 15 seconds.

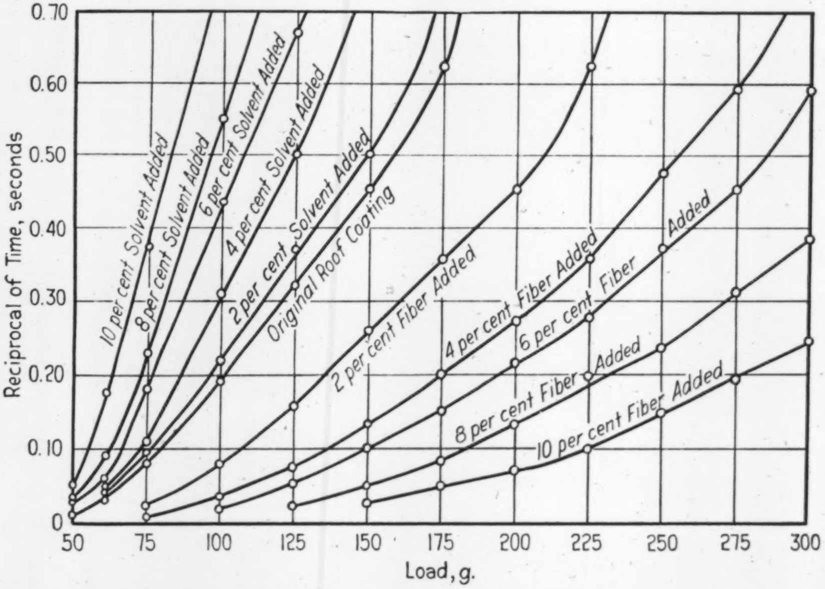

FIG. 4.—Results of Tests Made on Sensitivity of the Consistometer with Fibrous Roof Coatings.

During this work it was found that the apparatus could be used to indicate the homogeneity of the sample. Poorly mixed material gave wide differences between single determinations. This same material when reground and thoroughly mixed gave entirely satisfactory check results.

Sensitivity of the Consistometer with Fibrous Roof Coatings:

The sensitivity of the consistometer for testing fibrous roof coatings, when using the device shown in Fig. 2, was determined in a manner similar to that used on putties. A standard asphalt fibrous roof coating was taken as a base and to separate samples were added varying percentages of solvent and fiber. Consistency results were obtained with a wide range of loads. The results indicate the apparatus to be sensitive to as low as 2 per cent variation in the solvent content and less than 2 per cent in fiber variation. The results are shown in Fig. 4.

TABLE III.—RESULTS OF TESTS ON TWO SAMPLES OF ROOFING PUTTY.

SAMPLE A

TEMPERATURE	CONSISTOMETER RESULTS	
	LOAD, 75 G.	LOAD, 100 G.
68° F. (20° C.)	12.0 sec.	5.0 sec.
77° F. (25° C.)	7.0 sec.	4.5 sec.
86° F. (30° C.)	6.0 sec.	2.5 sec.

SAMPLE B

TEMPERATURE	CONSISTOMETER RESULTS		
	LOAD, 100 G.	LOAD, 150 G.	LOAD, 200 G.
68° F. (20° C.)	50.0 sec.	11.0 sec.	3.9 sec.
77° F. (25° C.)	49.0 sec.	10.0 sec.	3.8 sec.
86° F. (30° C.)	32.0 sec.	8.5 sec.	2.3 sec.

Effect of Temperature on the Consistency Test:

All of the tests reported were performed at a temperature of 77° F. (25° C.). In determining the suitability of the machine for factory control, tests were made on two samples of putty at temperatures of 68, 77 and 86° F. (20, 25 and 30° C.) under several loads. The results indicated that while temperature was important the test was not supersensitive beyond the point of practicability. The results are shown in Table III.

Tentative Specifications:

From the results shown in Tables I and II, tentative specifications of from 2 to 10 seconds, 150-g. load, were adopted for both putties and roof coatings. These specifications have been in effect in the author's company for a period of over one year and appear entirely satisfactory. In certain cases materials were found which tested as high as 14 seconds and which were considered usable but too stiff for general use. In practically all cases where samples tested below 2 seconds, the material was considered too thin for use.

Consistency Measurements on Various Brands of Roofing Putties.

In Fig. 5 are shown consistency curves for ten of the best known asphalt roofing putties on the market. These ten materials showed wide differences in consistency on practical trowelling tests and the results were verified by measurements on the putty consistometer. Putties C and F were considered too stiff for satisfactory application, and putties I and J much too thin. If the consistency results on these putties, with a 150-g. load, are compared with the tentative specifications of 2 to 10 seconds, or expressed as reciprocals of the time, 0.10 to 0.50, it will be found that four of the ten, or 40 per cent, are outside of the specified limits and likewise outside of the satisfactorily usable range.

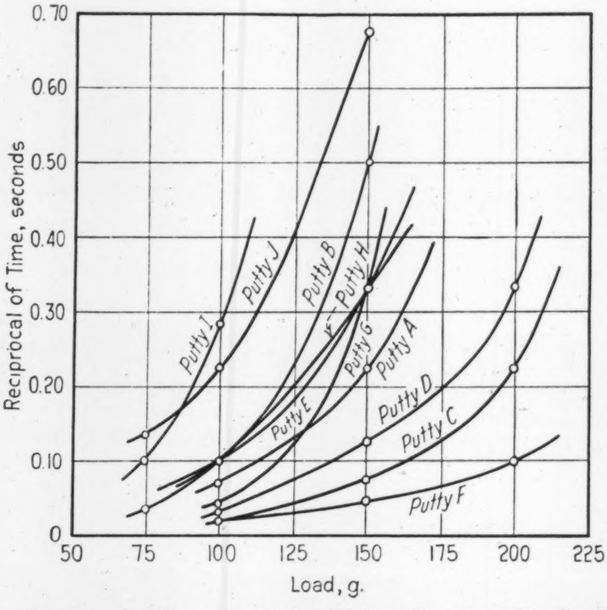

FIG. 5.—Consistency Measurements on Various Brands of Roofing Putties.

Application of the Consistometer to the Measurement of Miscellaneous Materials:

In addition to its designed use with putties and roof coatings, the apparatus is applicable to consistency measurements on a wide variety of miscellaneous materials. With the ball attachment it may be used to test semi-bodied or bodied oils, thin rubber cements, paints, lacquers, syrups, and similar materials. With the rod attachment the measurements can be carried to very viscous rubber solu-

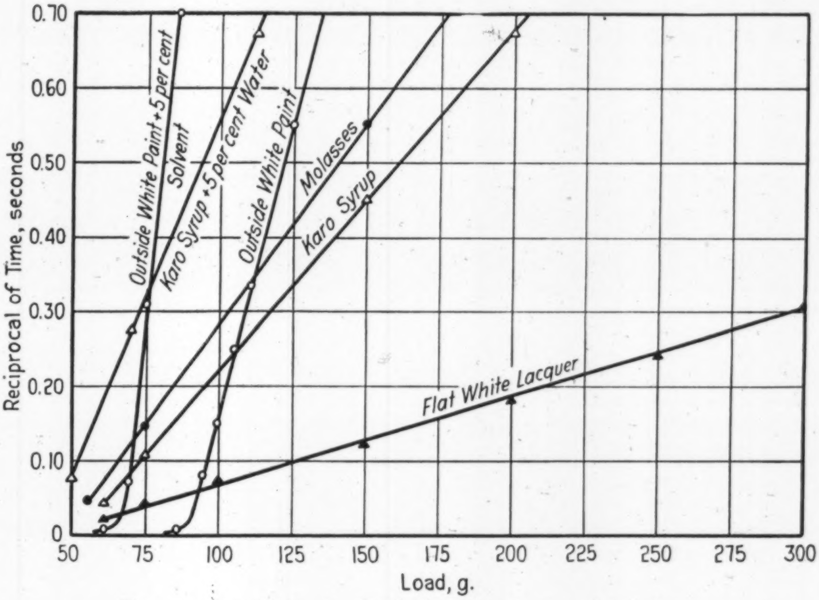

FIG. 6.—Consistometer Tests on Miscellaneous Materials.

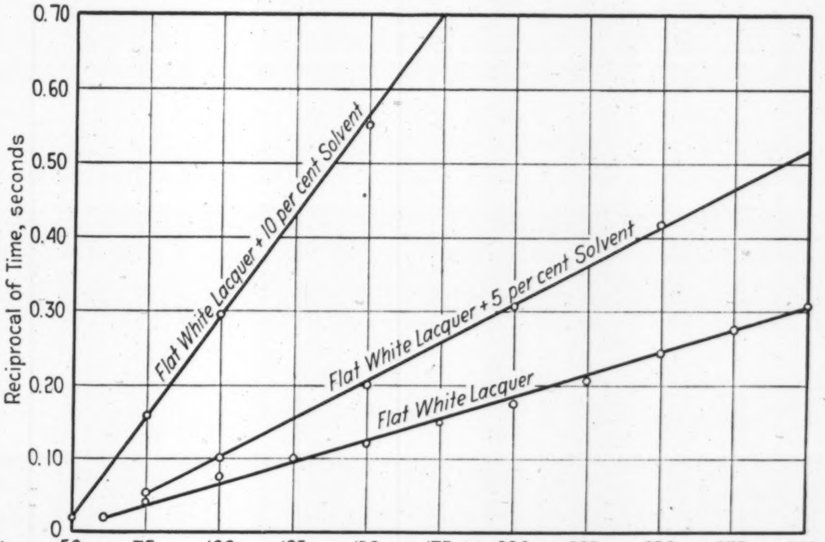

FIG. 7.—Consistometer Tests on Flat White Lacquer.

tions, heavy-bodied oils, and miscellaneous mixtures of trowelling consistency. Characteristic curves of a group of miscellaneous materials tested with the ball attachment are shown in Figs. 6 and 7. It is interesting to note the difference in the curves for the white paint and the white lacquer. The paint curve shows a definite plastic yield point and low viscosity as compared with the viscous lacquer. In Fig. 7 the sensitivity of the device in indicating dilution of the lacquer is shown. This same effect is shown with the paint and syrup in Fig. 6.

CONCLUSIONS

The differences in consistency of roofing putties and fibrous roof coatings as observed in practical applications are readily measurable with the consistometer described. The usual methods of varying the consistency of these products (by the addition of small quantities of fiber or solvent) produced consistency changes which were readily measurable and indicated the device to be sufficiently sensitive. The device itself is accurate, rugged, and relatively inexpensive, and is considered satisfactory for plant and laboratory use. The method is rapid, samples are easily and quickly prepared, and the apparatus easily cleaned.

Considerable differences in consistency exist between the products of different manufacturers, four out of the ten examined being considered either too stiff or too fluid for satisfactory use. Standardization of roofing putties and fibrous roof coatings on a consistency basis appears desirable and could be accomplished by general use of the apparatus described. Tentative specifications for consistency of both types of products are recommended as 2 to 10 seconds for a 150-g. load at 77° F. (25° C.).

The use of the device described is not limited to the measurement of consistency of roofing putties and fibrous roof coatings but may be successfully applied to the testing of a large variety of materials which are ordinarily difficult, or impossible, to measure with the standard laboratory equipment.

DISCUSSION

MR. P. H. WALKER.[1]—I wish to suggest the consideration of the use of an apparatus like the one described by Mr. Clarvoe in place of the penetrometer in testing asphalt. I have an idea that better results could be obtained if, instead of using the needle, which is quite hard to get, one used a cylinder and a larger load.

MR. G. W. CLARVOE.[2]—In that connection I may say that we are planning to do considerable work along that line. The apparatus is very satisfactory for measuring the consistency of bituminous materials in the liquid state, and by surrounding the cylinder with a heating coil, we expect to get measurements of the consistency of the material at the application point, such as pipe coatings and material of that kind. I think that Mr. Walker's suggestion is very good.

MR. C. S. REEVE.[3]—A number of us have been working along the line suggested by Mr. Clarvoe for quite a few years in an effort to find some suitable means for specifying fibrous roof coatings, and I am sure that we shall all be interested in trying this method to see whether he has solved a problem which I feel none of us has altogether successfully solved so far. I am very much interested in the specifications he has suggested here, and if Mr. Clarvoe can evolve a specification that will be generally acceptable to the purchaser of plastic material, he will have done a really good job. However, there is so much personal preference in this matter that we have found it almost impossible to meet the several demands for plastic material; the same product is entirely too thin for one fellow and entirely too thick for another and just right for the third man. We will take a real interest in trying this apparatus and in comparing the results on our own products with the specifications he has set up.

MR. CLARVOE.—Answering Mr. Reeve's comment, we have had this apparatus in use for almost a year in our company and have been governing the manufacture of our product entirely by these specifications.

MR. J. M. WEISS.[4]—Referring to Figs. 6 and 7 of the paper, where the results are well above the yield point in all the determinations, would it not be more informative if the results were expressed as the angle of the straight line? That is really the measure of absolute consistency, and if you were going to place a requirement in a specification and could express it as the angle, you would have a very definite thing, far more definite than a statement in seconds, because some of the curves cross each other. If you happened to pick a particular point where two lines crossed, you might have two entirely different types of material, and simply because you picked that one point, you would show them as identical where, in reality, they would be very different.

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[1] Chemist, U. S. Bureau of Standards, Washington, D. C.

[2] Asphalt Chemist, Research Laboratory, Johns-Manville Corp., Manville, N. J.

[3] Manager, Research Development, The Barrett Co., New York City.

[4] President, Weiss & Downs, Inc., New York City.

MR. CLARVOE.—I think the suggestion of Mr. Weiss is very good; I think a lot could still further be done along this line in the way of interpreting the results; we consider this merely preliminary work.

MR. H. C. PORTER.[1]—This apparatus interests me a good deal in connection with some work I have done on the consistency of coal at its softening point. That is a difficult problem because coal decomposes at its softening point and during the test the material is changing all the time. In this apparatus, I should like, particularly, to ask about the temperature control. I see that the cylinder is brought to a constant temperature of 77° F. (25° C.), but I do not see any means provided for keeping it there during the test. With coal, that is extremely important, to get the temperature change along with the change in consistency. Dr. Kurt Baum, in Germany, has devised an apparatus for testing the consistency of coal ash at its fusion point, getting the clinkering quality of the ash by a method similar in principle to this. He has a little cylinder of the coal ash heated slowly in the furnace, a piston resting on it, and as the piston sinks upon the softened material, the motion is amplified by a long arm on a fulcrum and recorded on a revolving chart. He thus gets a characteristic curve showing the changing consistency of his coal ash as it softens.

MR. CLARVOE.—The control of temperature during the test is purely a matter of choice, and I think the apparatus is very adaptable to temperature control; in testing materials where we want extremely accurate temperature control, we can set the apparatus to the proper depth in a constant temperature bath. In making these tests we used a temperature of 25° C. (77° F.) which is close to room temperature, and we got such a small change in temperature, even standing for half an hour in the laboratory, that we did not consider such a procedure necessary. With a suitable bath and immersing the apparatus to the proper depth, you can control the temperature at any point you wish. By wrapping the cylinder with electrical heating coils you can control it at higher temperatures.

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[1] Chemical Engineer and Chemist, Philadelphia, Pa.

MR. J. S. MILLER, JR.[1]—I regret that Mr. Clarvoe did not tell us more of his preliminary work and whether he tried attachments to the penetration machine or modifications of any other piece of available apparatus, and if so why they were discarded.

The field of testing bituminous materials is becoming more complicated each year in our endeavor to learn more of the properties of such materials, yet we should strive to adapt apparatus at present available in so far as that is practicable or else our testing will become a mass of variable methods and apparatus and thus defeat simplification. There will always be those who will include new methods of test and at the same time retain old methods of test which will seriously complicate this field, and every effort should be made to adapt the older apparatus when and if possible.

MR. H. A. GARDNER[2] (*by letter*).—Although no mention is made in this paper, the author is surely aware of the Gardner-Parks Mobilometer which was first announced by the writer and H. C. Parks in *Scientific Section Circular No. 265*, Paint Manufacturers' Association of the United States, in April, 1926. Several additional papers have also been published on the use of this device to which the author's is strikingly similar. The only important changes the author has made are two: first, use of the stem alone without any disk; and second, the substitution of a ball for the disk. These changes are obviously desirable for use with materials containing fibrous matter. The present Mobilometer could be used in the same manner by the use of a longer guiding collar for the stem.

Regarding the use of the Mobilometer for determining the brushing properties of protective coatings, Williamson, Patterson and Hunt[3] prepared curves similar to the author's, using a Bingham-Murray plastometer. It is obvious also that the Mobilometer will yield the same data.

The Mobilometer is already being used for determining the consistency of paints, etc., lubricants, ceramic slips, tooth pastes, and food products such as mayonnaise, catsup, etc. The Mobilometer may be used for unlimited consistency determinations by incorporating various obvious adapters.

MR. CLARVOE (*author's closure by letter*).—Replying to Mr. Miller, at the beginning of this work our problem concerned primarily the development of an apparatus and method for measuring the consistency of roofing putties. We were not concerned, at that time, with the problem of measuring the consistency of roof coatings, and it is only incidental that the putty apparatus could be easily adapted for this use. It is recognized that the measurement of roof coating consistency might be accomplished by other methods developed as modifications of apparatus at present available. This could not be done in the case of the putty consistometer.

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[1] Director, Technical Bureau, The Barber Asphalt Co., Maurer, N. J.

[2] Chemical Engineer, The Institute of Paint and Varnish Research, Washington, D. C.

[3] *Industrial and Engineering Chemistry*, Vol. 21, p. 1111 (1929).

Available devices operating on four different basic principles were examined and rejected. These, together with the reasons for rejection appeared so obvious that it was not considered necessary to give experimental results. Actually, we were rejecting the principle as well as the device in question and considered that all similar devices operating on like principles would be unsatifactory for similar reasons. A great many devices were rejected without experimental tests being made because visual examinations or descriptions indicated that they would not meet the requirements which we felt such a device would be called upon to meet. Experimental evidence was not necessary in order to determine that a device was complicated, fragile, or that a long time would be required to complete a single test.

Replying to Mr. Gardner, unfortunately, at the time this paper was written we were not aware of the apparent similarity of the Gardner-Parks Mobilometer and the present device. Mr. P. H. Walker, of the Bureau of Standards, pointed out this fact prior to the presentation of the paper at the June meeting, and a brief discussion of the similarities and differences of the two machines was given at that time.

In principle, there is no similarity between the two devices. The Mobilometer operates on the principle of a multiple orifice viscosimeter, and in this category falls into the class of orifice viscosimeters. These were rejected because of orifice clogging when testing fibrous materials. The present device is based upon the principles of the falling cylinder and falling ball viscosimeters. The putty consistometer was based upon the apparatus of George A. Smith for measuring the workability of concrete[1] and the roof coating consistometer developed as a later modification of that apparatus.

It is entirely possible that the Mobilometer could be rebuilt to operate similar to the author's device. Such rebuilding would necessitate the redesign of the plunger rod, the guide sleeve arrangement, and the sample container which is considered of too small bore for proper filling. In addition, the mechanical release mechanism would be desirable, if not actually necessary, in order to obtain an instantaneous release for the plunger without side function on the sleeve, or without chattering.

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[1] George A. Smith, "The Measurement of Workability of Concrete," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 505 (1928).

A MACHINE TEST ON THE DURABILITY OF MANILA ROPE

By N. C. Wiley[1]

Synopsis

A study by the Navy Department of available service and machine durability test data indicates the desirability of more reliable information as to the effect on the performance life of possible variations in fiber grade, oil content, lay, yarn size, etc. Recent developments indicate the realization of such a need on the part of other consumers and manufacturers. Information at hand casts doubt on the assumption that the rope having the highest breaking strength will necessarily wear the longest under service loads.

Because of the importance of manila rope to the Navy an investigation now being conducted is described in which the relative durability of ropes differing in fiber content is being determined by machine durability tests and by service tests. It is hoped from the data obtained to determine the machine conditions from which relative results will be obtained approximating the relative results obtained in service. Using the machine durability method thus arrived at it is proposed to study one at a time the variables concerning which there is now lack of informed and well-supported opinion. In each study enough tests of rope made under normal conditions will be run to insure results that are truly indicative of the variable being studied. The information obtained will be applied not only to rope for the Navy but to the further development of the Federal specification for manila rope.

Introduction

This paper describes a machine for testing the durability of manila rope recently placed in operation at the Navy Yard, Boston, Mass., where manila rope used by the Navy is manufactured. Tests on this material have recently received scant attention in published literature. There is not full agreement between manufacturers and consumers as to the specification for a manila rope of optimum durability. Not all who have given thought to or had experience with the problem are convinced of the value of machine durability tests in arriving at this optimum specification. For these reasons the descriptions of the machine at Boston and of the tests which are to be made with it are prefaced with a review of the developments which culminated in the decision to build a machine and which influenced its design.

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[1] Associate Materials Engineer, Bureau of Construction and Repair, Navy Department, Washington, D. C.

The Bureau of Construction and Repair of the Navy Department has jurisdiction over the technical aspects of material procurement for and manufacturing methods at the Boston rope walk. It designs the blocks and other gear with which rope on Naval vessels is used and determines the factors of safety in boat falls, the sizes of hawsers, etc. An officer in the Construction Corps is Chairman of the Cordage Committee of the Federal Specifications Board. The Bureau has therefore found it necessary to give careful consideration to manila rope problems and has been in a position to coordinate information obtained from the dual viewpoint of producer and consumer.

TABLE I.—GRADES OF MANILA FIBER.

Grade	Color	Cleaning	Length	Size	Texture
	GRADES ACCEPTABLE IN SPECIFICATION ROPE				
E	Very light ochre mixed with ivory yellow	Generally excellent	3.4 to 7.7 ft.	Fine	Soft
F	Light ochre or very light brown	Excellent	3.4 to 7.7 ft.	Fine to medium	Soft to medium soft
S_1	Light ochre with a few streaks of light red or light purple	Excellent	23.6 in. to 3.4 ft.	Fine	Soft
I	Very light brown	Good	3.4 to 7.7 ft.	Fine to medium	Medium soft
S_2	Ochre or very light brown with light red or light purple streaks	Excellent	23.6 in. to 3.4 ft.	Fine	Soft
J_1	Light brown or dingy white	Good; rarely fair	3.4 to 7.7 ft.	Fine to medium	Medium soft
	GRADES NEXT LOWER THAN ACCEPTABLE GRADES				
G	Mixture of dull brown, light green and brown	Not so clean as S_2	23.6 in. to 3.4 ft.	Medium fine	Medium soft
S_3	Light purple or light red mixed with a small proportion of light	Excellent	23.6 in. to 3.4 ft. Mostly short	Fine	Soft
J_2	Dingy light brown or dingy light yellow	Fair	3.4 to 7.7 ft.	Medium to bold	Medium

This discussion will be confined to the consideration of 3-strand rope of 2-in. circumference and larger, as such rope involves only one fiber mixture. The grades of fiber now used, and the grades next below, are described in Table I. The relative proportion which so-called higher grades bear to total fiber produced is slowly decreasing and this fact has been reflected in changes in the grades used. Prior to 1928, the Boston rope walk used no fiber tagged lower than Grade I or S_2, and mixtures containing more than 50 per cent of these grades were not used. If this restriction were now in effect, the bulk of the rope used by the Navy would have to be made from about 6 per cent of the abaca fiber exported from the Philippines. The rope now considered standard results from mixing two bales of grade F or S_1, four bales of I or S_2 and one bale of J_1. As the normal cost of the lowest of these grades is less than 70 per cent of the cost of the highest, and the cost of material is about 60 per cent of the cost of rope, the economy of determining the lowest grades or mixtures which will not result in a decrease of strength or durability is obvious.

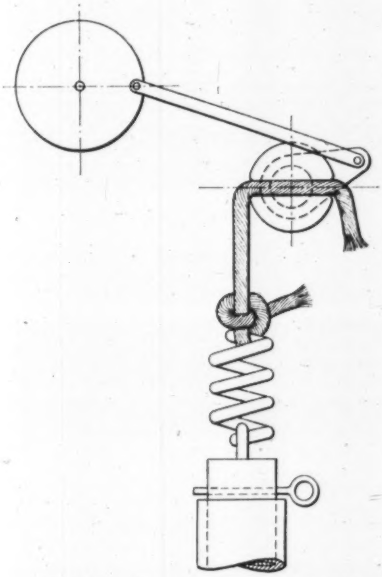

FIG. 1.—Machine Developed by E. W. Brewster.

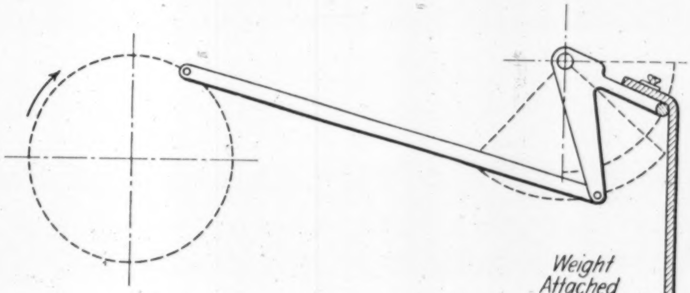

FIG. 2.—Machine Designed at the Bureau of Standards.

DURABILITY TESTS ON ROPE YARN

Efforts of other investigators were first directed at a determination of the relative durabilities of the individual yarns from which the strands of a rope are made, presumably because of the obvious economy of such tests as compared with tests on rope.

In 1925 Schoffstall and Boyden described a machine shown diagrammatically in Fig. 1, developed by Mr. E. W. Brewster. The angle of oscillation was 108 deg. and the speed 480 complete oscillations per minute. Retaining the same principle, these investigators designed, at the U. S. Bureau of Standards, the machine shown in Fig. 2. They settled on a 90-deg. angle of oscillation with the cross arm vertical at the top of its stroke and a speed of 110 oscillations per minute, using a load of 18 lb. with a No. 18 yarn. A degree of accuracy of approximately 5 per cent was obtained from 30 specimens.

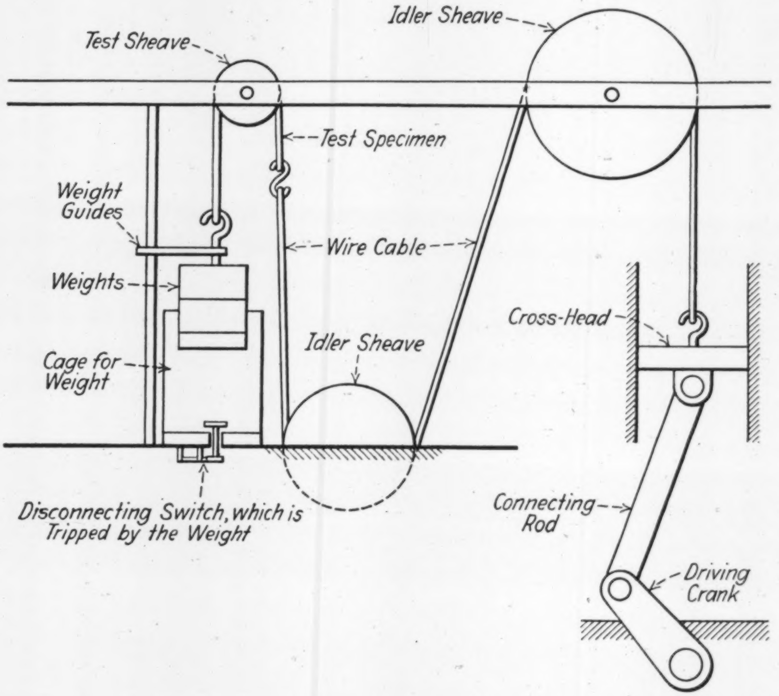
Idler Sheave
Test Sheave
Test Specimen
Weight Guides
Wire Cable
Weights
Cross-Head
Cage for Weight
Idler Sheave
Disconnecting Switch, which is Tripped by the Weight
Connecting Rod
Driving Crank

FIG. 3.—Diagrammatic Sketch of the Bureau of Standards Endurance Machine.

Tests of yarn on this machine yielded results which showed logical groupings in regard to twist, size, and oil content, but the attempts to differentiate between grades showed an overlapping between the so-called higher and lower grades. In the light of information then available, it was thought that this overlapping indicated the necessity for further investigation on full-size ropes, and such tests were made on two somewhat dissimilar types of apparatus, which had been developed at the Bureau of Standards and at the Plymouth Cordage Co.

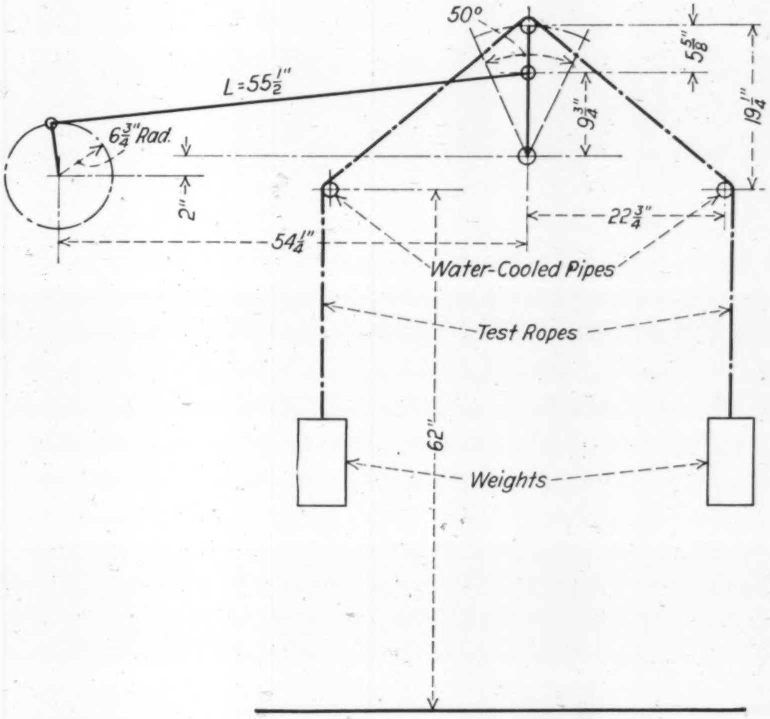

FIG. 4.—Diagrammatic Sketch of Plymouth Machine.

DURABILITY TESTS ON ROPE

For these tests 3-strand rope of 2¼-in. circumference was made at the Boston Navy Yard with eighteen variations as to fiber content. The Bureau of Standards' machine, shown diagrammatically in Fig. 3, caused the test rope, which was bent over a sheave of 9-in. outside diameter, to raise and lower a weight of 665 lb. about thirty-three times a minute until the rope broke. Four specimens of each grade or mixture were thus broken.

In the Plymouth machine the ropes were bent over a 1½-in. diameter, water-cooled, cold-rolled steel tube through an average

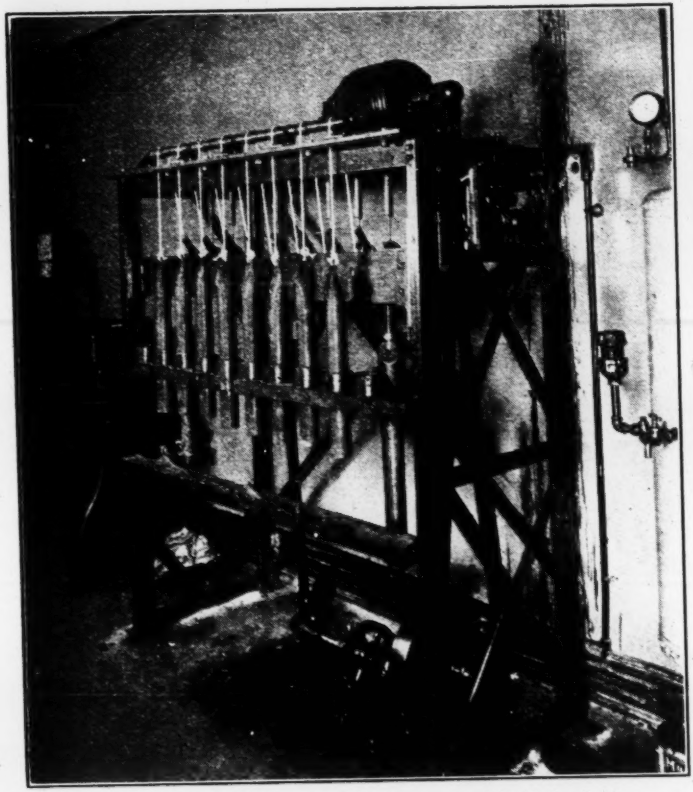

FIG. 5.—Machine Used at the Bureau of Standards for Durability Tests.

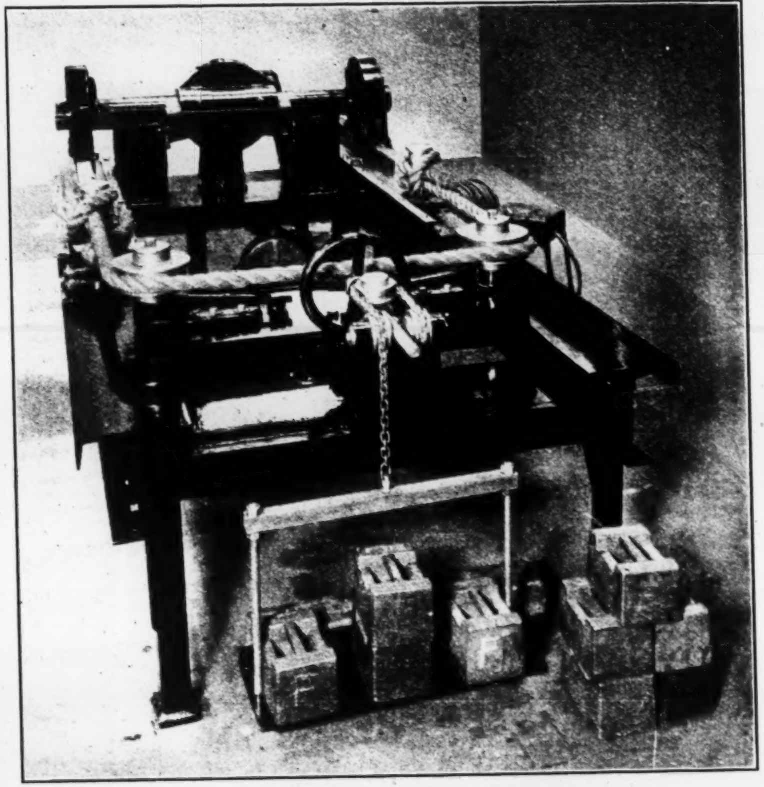

FIG. 6.—Manila Rope Testing Machine.

angle of approximately 45 deg. Eight ropes could be tested at a time. A weight of 60 lb. was suspended from each rope which made 40 complete oscillations per minute until the rope broke. This machine is shown diagrammatically in Fig. 4. Two specimens of each grade or mixture were broken on this machine. At the time of these tests neither of these machines operated under conditions of constant humidity or temperature. Due to these variables and to variations in size and oil content between the several grades of test rope, the number of tests on each grade was considered to be insufficient to warrant final conclusions from the results obtained. The order of results of the unmixed grades in which the variables in the rope were within the most reasonable limits were H, J_1, S_2, J_2, I, F and E at the Bureau of Standards and J_1, H, J_2, S, E, F and I at Plymouth. The similarity of these orders is of interest and when considered together were thought by the Bureau of Construction and Repair to warrant a further investigation of the relative endurance of these grades.

SERVICE TESTS ON ROPE

The next tests made were practical service tests on ropes each consisting entirely of one of several grades on which comparisons were particularly desired. After ascertaining that such variations as lay, yarn size and twist, diameter and oil content were within reasonable limits, 8 test ropes were put in service, four of which were 3-strand, 5½ in. in circumference, and four 4-strand, 4 in. in circumference. Each of these groups contained ropes made entirely of grade F fiber, of S_1, of J_1 and of G. The extreme variation in oil content was less than 2 per cent. The 5½-in. ropes were placed in service on 2-yd. tugs and the 4-in. ropes on the forming and laying machine drives in the rope walk. Both tug and walk ropes were given as much service as is usual. The G ropes had the highest initial strengths. After removal from service the ropes were again tested and the average loss in strength found to be 29 per cent for J_1, 32 per cent for G, 33½ per cent for S_1 and 42 per cent for F. These tests showed two types of practical service to check as to order of results with two types of durability tests, all showing J_1 to possess more durability than F. It therefore appeared that properly conducted laboratory durability tests could be used definitely to determine the value of a fiber grade as compared with a uniform standard.

VARIOUS DURABILITY MACHINES

Before deciding on the design of a machine for the Boston Navy Yard, consideration was given to various machines used for similar purposes. The machine shown in Fig. 5 was recently used at the Bureau of Standards for durability tests on Nos. 7 and 8 sash cord and on No. 20 manila yarns. A similar machine is used by the Silver Lake Co. at Chattahoochee, Ga. The Bureau of Standards' machine is located in a room kept at 65 per cent relative humidity and 70° F. The Chattahoochee machine operates under varying temperatures and relative humidities, and with lighter loads, larger sheaves and slower speeds than at the Bureau of Standards. Recent tests with these machines on similar sash cords showed variations in durability as between finished and unfinished cords in which the order of durabilities led to similar conclusions.

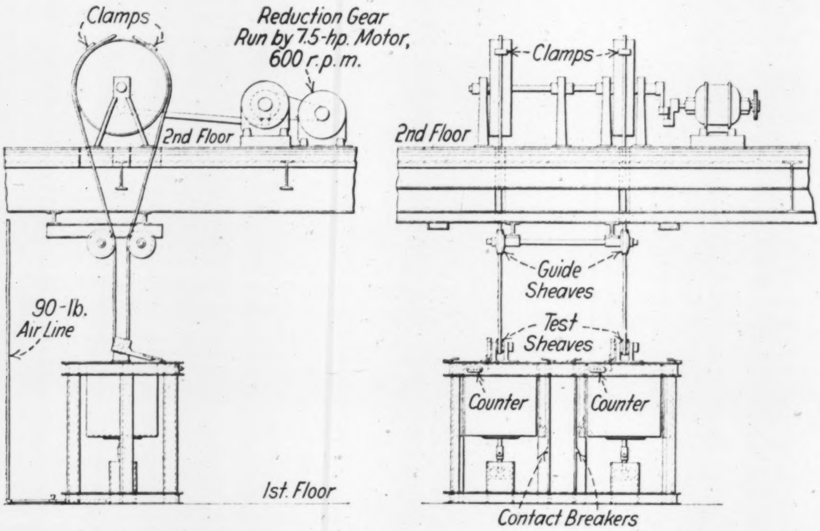

FIG. 7.—Durability Machine Used for Testing Rope at the Boston Navy Yard.

In one manila rope testing machine recently built, Fig. 6, the rope travels a distance of 3 ft. in a horizontal plane, turning through an arc of 90 deg. at each of two horizontal sheaves of 7-in. outside diameter. These sheaves are mounted on a sliding carriage to which is attached the hanging counterweight which keeps the load on the rope. The machine is operated at 40 oscillations per minute and loaded to give a factor of safety of 10 on the rope. These operating conditions provide pronounced heating of the rope. Humidity is controlled. The machine is reported to have yielded valuable information, especially on rope lubrication.

A machine for testing rubber belts, with five test sheaves for

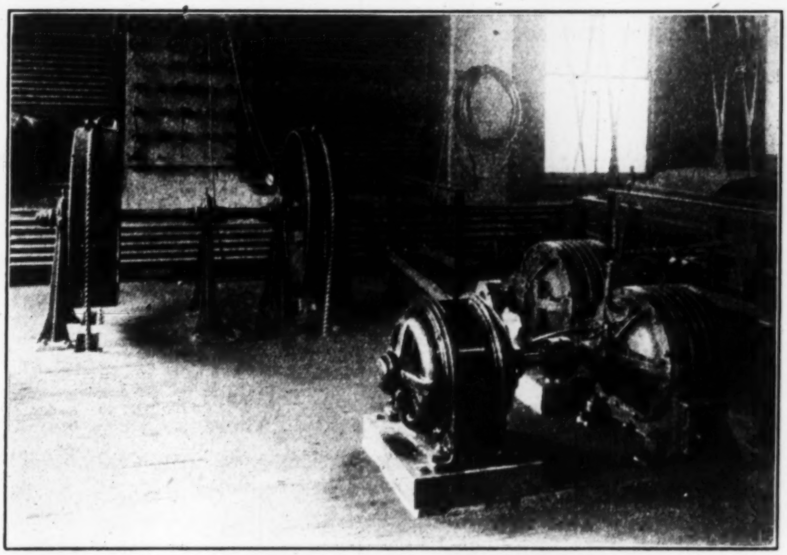

FIG. 8.—Upper Floor View of Durability Machine.

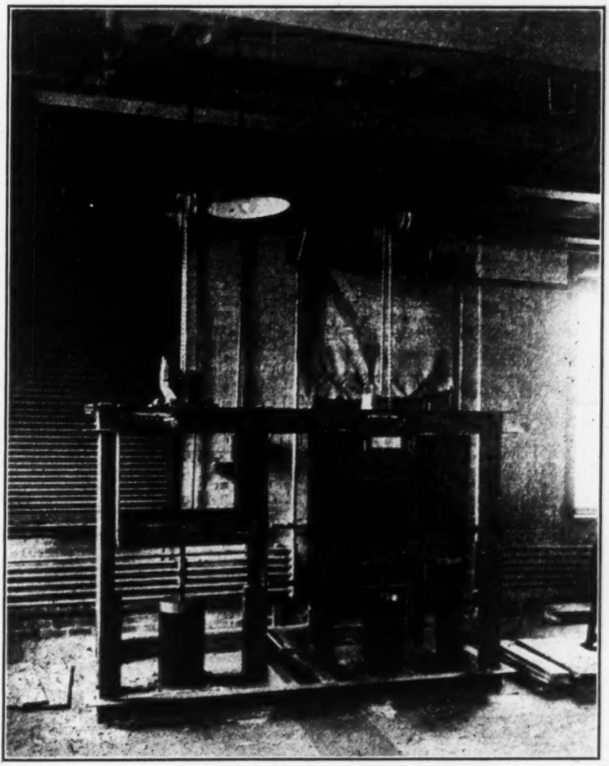

FIG. 9.—Lower Floor View of Durability Machine.

testing as many specimens simultaneously is described in the 1926 report of the Society's Committee D-11 on Rubber Products.[1]

DURABILITY MACHINE AT BOSTON

The rope durability machine at the Boston Navy Yard is shown in Figs. 7 to 9, and details of a test sheave in Fig. 10. The weights, test sheave and recording apparatus are in a ground floor room about 15 ft. square. The driving mechanism is directly above on the second floor. The utilization of two floors has resulted in an appreciable economy in the cost of the machine and in the size of the space to which humidity control need be applied.

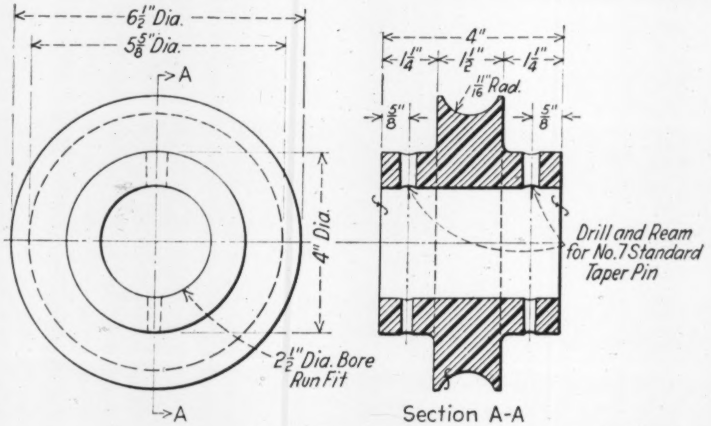

FIG. 10.—Details of Test Sheave.

The 7.5-h.p. motor shown in Fig. 8 oscillates the drums to which the ends of the test ropes are clamped. The speed can be varied from 1.5 to 8.0 oscillations per minute by interchanging sprockets on the reducer shafts. The angle of oscillation of the drums is such that the travel of each test rope is 36 in. The portion of the rope normally on a sheave completely leaves the sheave on either side during a complete oscillation. A test rope is about 25 ft. long.

The tension boxes shown in Fig. 9 weigh 1121 lb. each when empty, which includes the weight of the box, sheave and dash pot piston. The load desired for a given test is made up by placing in the boxes steel flat bars weighing 60 lb. each. When putting in a new rope, the tension boxes are lifted by applying air to the under side of the dash pot.

The number of oscillations to failure of each rope is recorded on a counter on the front of the machine. Each counter is actuated by an extension arm attached to one end of the sheave pin. Frictional contact between the arms and the moving sheave pins causes the arms to raise and lower during each oscillation and the correct operation of the mechanism is unaffected by degree of rotation or creep of the sheave pins. The machine is wholly automatic after two ropes have been started together. The number of oscillations of each is recorded, but the machine continues to operate at uniform speed until the second rope breaks, when it automatically shuts off.

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 26, Part I, p. 474 (1926).

The ends of the ropes are secured to the periphery of wheels instead of to the extremities of walking beams because the latter design would cause a slight up and down movement of the tension boxes during operation which it is desired to avoid.

The use of two independent sheaves and tension boxes enables two ropes to be tested simultaneously, and therefore under identical atmospheric conditions. Thus a series of comparative tests can be run with two ropes which intentionally vary in only one respect, as grade, oil content, turn of strand, etc.

Relation of Tests to Boat Falls:

One of the most important uses to which manila rope is put by the Navy, or, indeed, on merchant vessels, is that of boat falls. One important difference between Naval vessels and other vessels, however, is that the ships' boats, and therefore the falls are used more frequently. The weights of ships' boats and the design of blocks have been carefully standardized. Essential limitations on davit heights and on weight place limitations on block sizes and on the number and size of sheaves. These limitations in turn limit permissible rope sizes and factors of safety and necessitate appreciable rope bending stresses at the sheaves. The combined result is an unavoidably severe service which results in short life of the rope. The high cost of replacements, the disastrous possibilities of failures and the large proportion of the total naval manila rope used in boat falls made it seem highly desirable to duplicate in a machine, as nearly as practicable, the action of boat falls on a rope. This has been accomplished by using for each size of rope a sheave the score of which duplicates a block sheave for the same rope size. Adjustable guide sheaves above cause the rope to make a 180-deg. turn around the test sheave. There are no reverse bends in the portion of rope under test nor are there in the hoisting parts of a boat fall.

Working factors of safety on boat falls, according to the latest instructions, including allowances for rope bending and friction but not for acceleration, are not less than 11. On some existing installations, however, this figure is somewhat less. In view of this, it has been decided to run the first series of comparative tests at a factor of safety of approximately 10, using the latest specified minimum strength of rope and allowing 10 per cent for friction in the sheave and for bending stresses in the rope.

On preliminary runs it was found that the number of oscillations to break did not approach those obtained at the Bureau of Standards on Boston made rope loaded to approximately the same factor of safety. The apparent reason is differences in the ratios of sheave diameter to rope diameter. The question of diameters had been investigated by the Bureau of Standards and they had adopted diameters at a point where any appreciable further decrease in sheave size resulted in a much greater rate of decrease in rope durability. At Boston, block-size sheaves, giving a ratio to rope size of about half that used at the Bureau of Standards were adopted as representing the most common service condition. In preliminary tests so far made at Boston on 3½-in. circumference rope, the ratio of diameter at base of score to diameter of rope is 4.8.

Speed of Operation:

The remaining variable in machine operation was speed. The speeds at which the first tests were run showed a marked heating of the rope due to internal friction caused by bending. By means of a fine-wire thermocouple wrapped spirally about the rope in the groove of the lay and securely taped to keep it in place, it was determined that with rope loaded to a factor of safety of 7, three oscillations per minute resulted in a temperature in the rope of about 130° F. A speed of 1.5 oscillations per minute resulted in a temperature of 100 to 105° F. As the machine is now geared to run at 1.5, 1.8 or 3.0 oscillations, it is evident that 1.5 is the highest speed which can be used at a rope size to sheave diameter ratio of 4.8 without causing appreciable heating of the rope, and tests are at present being run at this speed. At 1.5 oscillations per minute there is no appreciable loss in moisture in the portion of the rope passing over the sheave. This was determined after 180 oscillations and after 258 oscillations by weighing, immediately upon stopping the machine, samples cut from the portion of the rope which had been passing over the test sheave and samples from a portion which had touched neither test nor idler sheaves. The samples were then conditioned for 24 hours at 65 per cent relative humidity. The increase in weight was from 4.3 to 4.5 per cent in all cases.

The question of whether heating of the rope should be allowed depends on the rope variable under investigation. The first variable being investigated at Boston is fiber grade. As it is probable that heat affects different fiber grades to about the same extent, it is not considered that additional information is obtained by using a speed causing heating, and the increased durabilities resulting from a speed not causing a temperature increase probably give more consistent comparisons. On the other hand, if the variable under investigation were lay or oil content, heat would be a more important factor in causing a difference in the durabilities of two ropes. For this reason a speed of three oscillations per minute would appear preferable to 1.5 oscillations. At the latter speed, with the rope loaded to a factor of safety of 7, it has taken from 150 to 250 minutes of operation to cause rope failure.

Humidity:

Humidity plays an important part in both the strength and durability of rope, both of which increase with increase of relative humidity. Humidity and temperature are both kept constant in the vicinity of the machines shown in Figs. 4 and 5. Humidity is controlled in the vicinity of the machine shown in Fig. 6. Durability is sufficiently sensitive to humidity to have caused, with the machine shown in Fig. 3, oscillations to break recorded in the morning to have a perceptibly lower average than that of afternoon breaks, where a large number of tests on rope of uniform quality were being run at the rate of two breaks a day.

In later tests on the same machine after automatically controlled humidity heads had been installed, more consistent results were secured than had been previously reported. Apparatus is therefore now being installed in a room being built around the portion of the Boston machine shown in Fig. 9, for the purpose of maintaining the relative humidity at not less than 70 per cent. This room will also be used to condition the specimens of yarn used in the daily determinations of yarn strength and yardage and also to condition specimens of rope prior to tension tests. In the past, without conditioning, daily strength averages of unconditioned yarn were considerably lower in the winter months than during the summer months. The uncertainty thus caused makes it difficult to ascertain definitely whether conditions other than relative humidity are affecting these averages.

Preliminary tests on the rope durability machine at Boston indicate a gain of approximately one per cent in durability for each increase of 2 per cent in relative humidity. However, these figures are based on an insufficient number of tests to be conclusive.

CURRENT TESTS ON FIBER MIXTURES

As previously stated, a mixture of $\frac{2}{7}$ grade F or S_1, of $\frac{4}{7}$ grade I or S_2, and $\frac{1}{7}$ grade J_1, is standard at the Boston Yard for ropes 2 in. or more in circumference. Machine and service tests already mentioned indicate grade J_1 to have greater durability than the other grades in the standard mixture. The most expensive of these grades s grade F. In order to definitely determine the relation between the durabilities of grades V_1 and F, the Yard has manufactured in in $3\frac{1}{2}$- and 4-in. sizes some experimental 3-strand medium laid rope containing $\frac{4}{7}$ grade I and $\frac{3}{7}$ grade J_1, that is, $\frac{2}{7}$ J_1 is substituted for $\frac{2}{7}$ F in standard rope. The 4-in. ropes are being used as boat falls on eight light cruisers in comparison with standard ropes by using experimental rope on one fall and standard rope on the other in some cases, and in the remaining cases by using rope on both falls containing one experimental strand and two standard strands. Four-inch 4-strand rope containing two experimental and two standard strands has also been installed as transmission rope on the laying side of the rope walk. One length of 4-in. four-strand experimental and one of standard rope are in operation on the forming side. Three and one-half inch 3-strand rope is to be tested in the durability machine at Boston.

The yarn from which the above ropes were made has been tested for durability at the Bureau of Standards in the machine shown in Fig. 5, using 30-lb. and 15-lb. loads. Yarn of grade K fiber was also tested and some rope of this grade is to be tested on the durability machine. The following data are given relative to these yarns:

GRADE	OIL CONTENT, PER CENT	STRENGTH, LB.	FEET PER POUND
2 F, 4 I, 1 J_1	13.6	253	300
4 I, 3 J_1	14.0	247	275
K	12.2	178	310

When these tests on yarn and rope are completed the relative durabilities of grades F and J_1 fibers should be definitely established unless unexpected inconsistencies are found when combined test results are analyzed.

Boat falls had already been used for comparative service tests to ascertain the relative merits of 3-strand and 4-strand rope. In these tests one boat was used on each of six destroyers. In service tests it is not practicable to test the rope to destruction. When a Commanding Officer is of the opinion that the rope undergoing test on his vessel is no longer serviceable, the rope is returned to the Boston Navy Yard. Here the strength of worn sections is compared with the original strength of similar rope. In addition, yarns from the outside of strands and from the center of strands are compared as to strength with the new yarns from which the rope was made. Although ship personnel may have different ideas as to when boat falls cease to be serviceable, thus causing differences between ships as to the loss in strength of rope as turned in, comparable results are obtained between experimental rope and standard rope used at opposite ends of a boat, operating under identical conditions and the same number of times. The average loss in strength of the rope or yarns may thus vary widely as between the cruisers from which they are turned in, but the average loss of strength in experimental rope as compared with standard rope furnishes a reliable criterion of durability.

PRELIMINARY MACHINE TESTS AT BOSTON

The machine durability tests on $3\frac{1}{2}$-in. 3-strand rope comparing two fiber mixtures are being further utilized to obtain data on the effect of sheave size. Only one third of the experimental and standard test rope will be run on the block size sheaves shown in Fig. 10, another third will be used with a sheave of $8\frac{7}{16}$-in. diameter at bottom of score and the remaining third with a sheave of $11\frac{1}{4}$-in. diameter at bottom of score. The diameters of these sheaves are in the proportions of 1, $1\frac{1}{2}$ and 2. It is proposed to make consecutive daily tests on either side of the machine with different size sheaves. For example, on one day a small and an intermediate size sheave will be used, on the next day an intermediate and a large size sheave and on the final day of a cycle a small and a large size sheave.

DEGREE OF UNIFORMITY OF ROPE AND TESTS

A point frequently called to the attention of investigators is that ropes undergoing tests should be identical except for the variable being investigated. This desired condition cannot be obtained with manila rope and in tests with which the author is familiar is not considered to have been approximated. As previously mentioned, durability tests on $2\frac{1}{4}$-in. Navy rope on the machines shown in Figs. 3 and 4 were not considered reliable largely because of variations between and within different groups of rope in other respects than that of fiber grade, which was the variable under investigation. The most important of these incidental variables are considered to have been yarn size and oil content. Since these tests, there has been an appreciable improvement in the uniformity of yarn size in Navy rope of regular production. However, the variation in daily averages is still such that more than 10 per cent of these daily averages vary more than 10 per cent from the monthly averages. The same is true of yarn strength. Possibly half of these variations, particularly in strength, have been due to lack of humidity control in the laboratory. In current production the variation in the oil content of rope is not over one per cent.

The variations in durability tests, on both rope and yarns, have been found to be several times as great in per cent of the mean as the variations in strength. Not over half of the results lie within 10 per cent of the mean in most series. With a variation of not over 40 per cent in the strength of yarns at varying humidities, durability results on yarns of the same size, with humidity constant, varied over 100 per cent. Similarly, in the durability tests on $2\frac{1}{4}$-in. rope, the variations between the average durabilities of groups was much greater than the variations in strength between the same groups.

The $3\frac{1}{2}$-in. rope of recent production and standard mixture with which preliminary durability tests have been made on the machine at Boston has the improved uniformity noted above over the $2\frac{1}{4}$-in. test rope of varying fiber grades which underwent durability tests at the Bureau of Standards and at Plymouth. With the $3\frac{1}{2}$-in. rope, at a factor of safety of 7 and with block size sheaves, a probable error of the mean in per cent of mean of 2.3 (Bessel's formula) has been obtained from 25 tests. Eight of these tests were at 39 or 40 per cent relative humidity and the average variation from the mean of these eight tests was nearly as great as that of the entire series.

Number of Tests per Variable:

When a factor of safety of 10 is used instead of 7 and when humidity control is placed in operation, this probable error may be reduced, but for determining the relative durabilities of ropes in which the only intentional variable is the substitution of $28\frac{1}{2}$ per cent of J_1 fiber for F fiber, it is considered necessary to reduce this probable error very considerably. This purpose should be accomplished by testing at least 30 specimens of each grade of rope on each of the three sizes of sheaves. This will necessitate the use of at least 180 test specimens or 90 runs of the durability machine. These figures are, of course, subject to increase or decrease based on analysis of results as the series progresses. It should be continued until each type of rope shows a distinct frequency curve and until the probable errors of the means are appreciably less than half the difference in average durabilities. In proposed future series on this machine in which the relative values of fiber grades G and S_3 are to be investigated, it is not the present intention to conduct concurrent service tests with boat falls and transmission rope. It will therefore be even more essential to insure that sufficient machine tests are made to insure accuracy in the difference of averages.

The above comments indicate that the problem of manila rope durability is being attacked in line with the theory of large numbers, and that no special precautions should be taken to insure a degree of uniformity in test rope above that achieved by normal production. By the use of this principle, changes in manufacturing practice made as the result of durability tests should result in approximately the increase in service life which the tests indicate.

SUMMARY AND CONCLUSIONS

Consideration of the results reported from the use of rope durability machines by several rope manufacturers, the Bureau of Standards and the Boston Navy Yard, leads to the opinion that quantitative conclusions should be the result of such a large number of similar tests as to preclude the use of a machine durability test as an acceptance requirement in rope specifications. It is considered, however, that a series of durability tests, supplemented where desired by service tests, can advantageously be used as the basis for modification of existing and proposed rope specification requirements.

Specific data on and conclusions as to the relative durabilities of grades of abaca fiber as determined by machine tests have been purposely omitted from this paper for the reason that no individual series of completed tests as yet available to the Bureau of Construction and Repair is considered to be conclusive, and it is believed preferable to use data at present available in support of final conclusions when tests now underway are completed.

Acknowledgments:

Acknowledgment is made to the Plymouth Cordage Co. for participation and advice in test work and for permission to describe yarn and rope bending machines designed by them; to the Whitlock Cordage Co. for a photograph and description of the durability machine they use; and to the U. S. Bureau of Standards for photographs and published and unpublished test reports which have been drawn on freely. Much of the data and reasoning in this paper originated with Mr. C. G. Lutts, of the Boston Navy Yard.

DISCUSSION

MR. M. F. SKINKER[1] (*presented in written form*).—About two years ago the Research Bureau of the Brooklyn Edison Co. began an investigation on manila rope somwhat similar in purpose to that in progress at the Boston Navy Yard. Limitations of present-day specifications, particularly the lack of a method for predicting performance, were responsible for the undertaking.

Ordinarily ropes are taken out of service before they actually break. This suggested a test for predicting performance by subjecting samples to a certain amount of wear, followed by a tension test to determine the loss of strength. A machine was built to subject ropes of medium size to repeated bending while under tension.

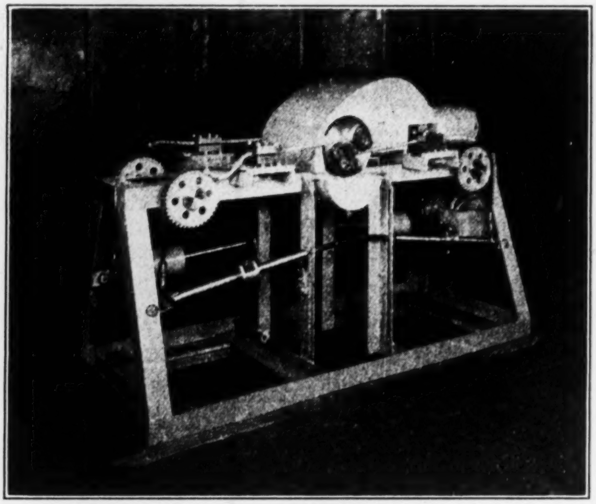

FIG. 1.—Side View of Rope Testing Machine.

The accompanying Figs. 1 and 2 show the machine with samples under test. The ropes are gripped between cross-heads which are connected to weighted lever arms by roller chains running over idler sprockets. The arms are pivoted to the frame so that tension adjustment is provided by changing the size or location of the weights.

Midway between the cross-heads can be seen a face plate to which are bolted two semicircular bending mandrels. The radii of the mandrels for various sizes of rope correspond to accepted minimum allowable sheave pulley diameters. The curved portions of the mandrels face each other, with the rope passing between. A $1\frac{1}{2}$-hp. motor oscillates the face-plate through an angle of 120 deg. 20 cycles per minute. This forces the rope to assume alternate S-bends and reverse S-bends while under tension. Provision is made for testing two samples at the same time. Tests can also be made on wet or alternately wet and dried ropes.

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[1] Assistant Director of Research, Brooklyn Edison Co., Brooklyn, N. Y.

Preliminary tests were made on two distinctly different types of rope, one quite soft and flexible, and the other hard and stiff. The results are shown in the accompanying Fig. 3. The soft rope was run at increasing tensions, an arbitrary figure of 15,000 cycles and then tested for loss of strength. It was found to have a flat characteristic with a sharply defined critical point at 250 lb. static tension.

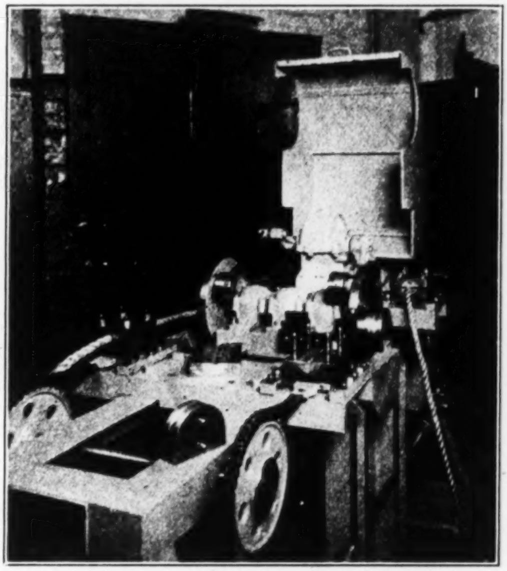

FIG. 2.—View of Testing Machine with Casing Raised to Show Interior Mechanism.

The hard rope would not last 15,000 cycles so the tests were made as above except at 10,000 cycles. This rope had a proportional characteristic and indicated much less resistance to wear than the soft rope although the initial strengths of both were exactly the same.

Further tests have been made on ropes from ten manufacturers. All were run at 10,000 cycles and the results were substantially the same as in the preliminary tests. However, the distinction is not quite so sharply defined and a third or intermediate group becomes apparent.

MR. B. H. FOSTER.[1]—What weakens the rope? Is it abrasion of fibers inside or outside of the rope?

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[1] Manager, Textile Section, United States Rubber Co., Passaic, N. J.

MR. SKINKER.—The wear in the machine we designed was entirely on the inside. When the strands are separated, shreds come out of the center. Having a reverse S-bend makes a lot of friction in between the strands for about 4 in.

MR. N. C. WILEY.[1]—The question of whether outside abrasion or internal wear results from the working of the rope over the sheave seems to depend to some extent on whether a sheave is used with a root diameter of score approximately that of the rope or whether a service sheave is used as in a block, which, of course, has a root diameter of score quite a little larger than the normal diameter of the rope to allow for the swelling of wet rope. The sheave used at Boston, as I stated, is a standard block sheave and it has a score larger than the rope, which flattens the rope. On the Whitlock machine—on the other hand—the root diameter of score is very close to the normal diameter of the rope. As you get closer to the normal diameter of the rope the wear is more largely internal but when the sheave flattens the rope you get more abrasion on the outside.

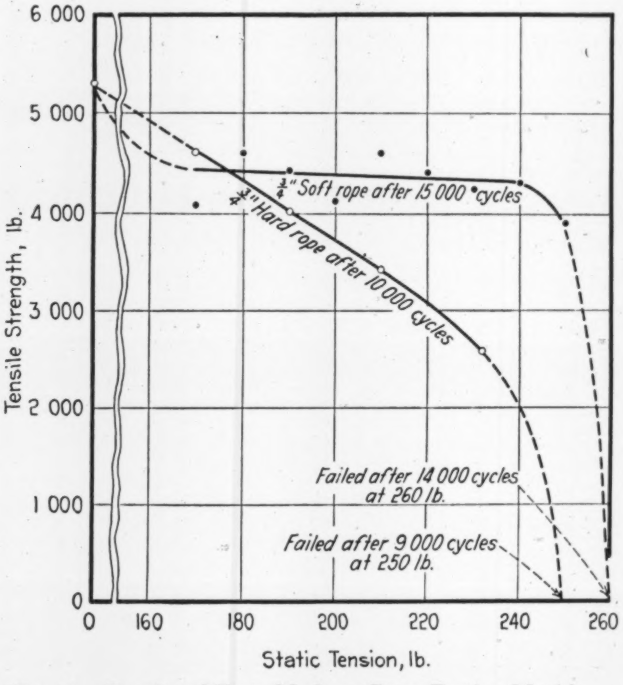

FIG. 3.—Results of Tests Made on Rope Testing Machine.

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[1] Associate Materials Engineer, Bureau of Construction and Repair, Navy Department, Washington, D. C.

ENZYME ACTION IN THE TEXTILE INDUSTRIES

By W. F. Edwards[1]

Synopsis

The main purpose of this paper is that of interesting the textile industries in a more comprehensive understanding of possible values that may accrue to them by a closer acquaintance with enzymes and their relation to some processes of manufacture, to mildews, etc., and more especially to their relation to the large and somewhat vague problem of improving textile fibers. To this end has been given (1) a brief historical résumé of the main facts, hypotheses and theories that have led to the name "enzyme" and to the classification and nomenclature of enzymes as used in the twentieth century; (2) a comparative study of amylase (diastase) from barley malt and fungi; (3) a brief statement of molds in cotton and wool goods and enzyme reactions; (4) a brief experimental study of possible practical uses of proteases such as pepsin, trypsin, papain, bromelin, korofor, serizyme and others in degumming silk in silk combinations with wool. It is shown that every indication leads to the conclusion that a competent knowledge of enzymes and their actions in processes of metabolism which are involved in vegetable and animal growth which must be carefully considered in any improvement of textile fibers, will be required of textile chemists and biochemists and a brief indication of training necessary is outlined.

Historical Introduction

A brief survey of fermentation processes is perhaps the surest way of understanding the origin of the term enzyme and the various phenomena ascribed to enzyme activities. Fermentation processes in the preparation of wine, vinegar, beer and bread were doubtless known and practiced in prehistoric times as indicated by certain references in written literature. These processes were, in all probability, looked upon as mystery processes perhaps akin to life processes in the animal and vegetable kingdoms, but were not limited to action on animal and vegetable matter. The philosopher's stone of the alchemists was supposed to set up a fermentation in the baser metals which might develop a germ or essence or whatnot under suitable conditions, to be found by trial and error methods, that should transmute or purify them into one of the noble metals, gold or silver.

The first step to definite knowledge on fermentation may be said to date from the latter part of the seventeenth century when Anton von Leeuwenhoek, a Dutch microscopist, sent to the Royal Society of London a description and drawings of yeast cells as seen by means of his recently devised powerful magnifier. However, it was more than a hundred years later, 1803, before Thenard, a French chemist, stated that fermentation was caused by the yeast cell and it was some thirty-five years later before the work of a number of investigators had brought forth convincing evidence that the yeast cell was the originator of fermentation and the yeast plant was given the name *saccharomyces* (sugar-fungus).

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[1] Director of Laboratories, United States Testing Co., Inc., Hoboken, N. J.

Liebig very soon (1840) attacked the doctrine that fermentation was caused by micro-organisms and announced the theory that fermentation was due to mechanical decomposition of complex substances and stated that yeast was a lifeless albuminoid mass. This theory held sway for more than fifteen years until Pasteur put forth his vitalistic theory by showing in a fairly conclusive way that fermentations and putrefactions were due to metabolism in micro-organisms. This vitalistic theory was followed soon afterwards (1858) by Traube's dictum that fermentation was due to different active principles (enzymes) produced by the yeast cell in its metabolic processes and not to the yeast cell itself.

However, the vitalistic theory still continued in favor and "true" ferments like yeast supposed to act by virtue of vital processes were called organized ferments in distinction from ferments like ptyalin, pepsin, trypsin, etc., which were considered as purely chemical products and called unorganized ferments. Much confusion arose over this classification as Traube's idea though not conclusively proved continued to persist which led Kuhne in 1878 to propose a new name for the unorganized ferments. The name was "enzyme" of Greek derivation meaning "in yeast" to insure including the unorganized ferments which were believed to be developed by the yeast plant. It was some twenty years later before the researches of Fischer, Buchner and others led to a convincing conclusion by an experiment carried out by Buchner (first published in 1897) in which he isolated from living cells a nitrogenous substance enzymic in character and which brought about identical fermentations without the presence of the yeast cells. He named the substance "zymase."

CLASSIFICATION OF ENZYMES

Most enzymes are soluble in dilute glycerol, sodium chloride solution, dilute alcohol and water and are precipitated by ammonium sulfate and absolute alcohol. They are mostly colloidal and act by catalysis. A textbook definition of an enzyme might be about as follows: An enzyme is an organic catalyst which is elaborated by an animal or vegetable cell and has the power of producing fermentation independently of the cells producing it. Buchner's zymase would be typical of the definition.

Each of the enzymes has an action more or less specific in character on which classification is based, that is, the action is specific as to the character of the substance on which it acts, usually termed its substrate. There are ten or more general classes, most of which are divided into several subclasses. The general classifications are quite varied, no two authors agreeing altogether, more or less on account of difference in point of view. There is more general agreement on the names in the literature which have as a first part an indication of the substrate and end in "lytic" or "clastic." As examples, amylolytic or amyloclastic enzymes are such as destroy or break down starches, dextrin, sugars, etc.; proteolytic or proteoclastic enzymes are such as destroy or break down proteins. To avoid confusion the endings "lytic" and "clastic" are now quite generally replaced by "ase" following Buchner's zymase, as amylase and protease for the above, and the subclasses under these would be called together the amylases and the proteases. Some of the amylases and proteases are the only enzymes which, with two or three bacterial ferments, have come into direct use in the textile industries, and in general to only a limited extent, notwithstanding that fermentation processes for the retting of hemp and for the degumming of silk have been in use for a long time. But these, like many other processes of the textile industries, have not been carefully investigated, it being only necessary to know that they work.

The best known and understood and most used enzyme in the textile industries is the amylase commonly known as diastase. It has been used under different trade names for a number of years for removing starch and dextrin from finished textiles but the optimum conditions of use such as temperature, concentration, pH value, etc., have not been carefully investigated so that there is no uniformity of practice.

Diastase is produced from germinating barley grains (malt-diastase) and from fungi. Taka-diastase is a trade name for diastase made from *aspergillus Oryzae* and has been perhaps more carefully investigated on account of its use as a pharmaceutical preparation for use in cases of amylotytic dyspepsia. Taka-diastase will convert one hundred times its weight of starch to maltose in ten minutes under favorable conditions which is much faster than the action of malt-diastase. Taka-diastase also produces a clearer and more liquid product than malt-diastase, which, however, may be due to other enzymes which have been found associated with taka-diastase.

Amylases are produced by many fungi of the *aspergillus* and *Penicillium* types but none, so far as the author knows, produce them in quantity proportionate to the taka-diastase produced by *aspergillus Oryzae*. Taka-diastase as a reagent for estimating starch sizing on cotton goods is compared to copper and iodine methods in an interesting paper in the *Journal* of the Textile Institute.[1]

A study of *aspergillus* and *Penicillium* molds sometimes spoken of as the green, black and yellow molds, though they are not the only molds of these colors, may be the most interesting studies for textile students as a means of becoming better acquainted with enzyme actions on account of their variety and their common occurrence in things relating to everyday life. The *aspergillus Oryzae* used in the production of taka-diastase is a yellow green mold. *A. flavus* is a yellow green mold found on preserves and jams in the home. *A. glaucus* is perhaps the most common green mold and *A. niger* is a very common black mold, both found everywhere, one might say. *Penicillium glaucum* is a green mold of somewhat different characteristics, but like *A. glaucus* it is found everywhere. *P. Roqueforti* is a green mold, the "ripening" agent of Roquefôrt cheese. *P. Camemberti* is a grayish white mold, the ripening agent of Camembert cheeses. *P. Italicum* is a blue-green mold found on oranges and lemons when rotting in storage together with *P. digitatum*, an olive green mold, and *P. expansum* is the storage rot fungus of apples and pears.

Fungi causing mildews in cotton goods are more often varieties of *aspergillus* and *Penicillium* than of other fungi. Identification of species of *aspergillus* causing mildew in cotton goods is given quite extensive consideration, including laboratory methods by Smith in the *Journal* of the Textile Institute.[2] The paper furnishes a quite considerable amount of information of interest to manufacturers and users of cotton goods and indirectly are useful to students of enzymes.

A very excellent paper on "The Fungi Causing Mildew in Cotton Goods" is written by L. D. Galloway, of the British Cotton Industry Research Association.[3] This paper takes up topics as follows: Occurrence of mildew fungi; source and extent of infection; methods of control; distribution of various types of mildew fungi (points out that *aspergillus* is more common in warmer southern United States and *Penicillium* predominates in northern states); the effects of mildew; identification of mildew fungi; and gives a three-page table of

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[1] R. G. Fargher and L. V. Lecomber, "The Determination of Starch in Sized and Finished Cotton Goods," *Journal*, Textile Inst., October, 1931.

[2] George Smith, "The Identification of Fungi Causing Mildew in Cotton Goods: The Genus Aspergillus," *Journal*, Textile Inst., March, 1928; February, 1931.

[3] L. D. Galloway, "The Fungi Causing Mildew in Cotton Goods," *Journal*, Textile Inst., June, 1930.

"mould fungi" isolated from cotton goods, naming the species of *aspergillus* or *Penicillium*, giving the source, as for examples, cloth mildewed abroad, cloth mildewed in England, raw cotton (Queensland), yarn from Texas, etc. Indirectly it is of interest to students of enzymes. Mr. Galloway has written another interesting short paper[1] on mildew fungi in which "diamond-spot" stains are considered and some interesting experimental suggestions are made.

It has recently been suggested in discussions of occupational diseases that a peculiar cough occurring now and then among cotton weavers is caused by a mildew, and some species of *aspergillus* mold is presumed to be the most probable cause. The author suspects that careful investigation might show that it was an enzyme of the mildew that is the active excitant of the cough which might be aggravated by the presence of spores.

The examples cited thus far all have to do with fungi and enzymes that are active in starches, dextrins, etc., and have stressed cotton goods (textiles made from cellulose). Starches, dextrins and cellulose all belong to the polysaccharide division of the carbohydrates. They are easily hydrolyzed to water-soluble products with the exception of cellulose which investigations seem to show has a much more complex molecule than starch. The damage done to cotton goods for the greater part is due to staining by colored spores or conidia or mycelia. Tendering is probably in most cases due to the action of bacteria in connection with mold or alone. Bacteria do not grow on pure cellulose as nitrogen is required for their growth which is also required for the production of enzymes by molds. Most, if not all cotton goods, have enough other substances present to furnish starting points for enzymes. Mixed wool or silk and cotton goods contain the nitrogen bearing substances essential to the production of enzymes. Wool and silk are favorable on account of their higher hygroscopicity. However, it should be noted that for some reason silk goods do not seem to be affected by molds and bacteria to the extent that obtains in cotton or wool or their combinations. Woolen textiles damaged in storage and shipping by mildews have been studied from time to time to a limited extent but in a general way it may be said that the investigations were attempts at short cuts to remedies and as in similar investigations for cotton goods, did not undertake to find and study the basal factors.

The stimulus for research investigations in the textile industries is too often unusual economic losses. The unusual epidemic of mildew in woolen textiles in storage in England in the year 1928 may be looked upon as a starting point for a somewhat extensive and to some extent more scientific investigation of this trouble. Burgess[1] of the British Research Association for Woolen and Worsted Industries undertook to find a remedy for this condition. He points out at the beginning of the first paper that micro-organisms are involved and that control of moisture content, temperature and ventilation cannot be adequate to prevent their action and proceeds to investigate the value of antiseptics while indicating that there are more purely scientific aspects of the subject. He indicates in the first paper some of the conditions such as moisture, alkalinity, acidity, etc., that favor or prevent the growth and action of the molds and bacteria studied and points out that, as in the case of cotton goods, the molds (fungi), do their main damage by developing colors and mycelia and that tendering is usually, though not necessarily, due to bacterial growths. In the second paper he furnishes several tables of data relating to results of growth of species of *aspergillus* and *Penicillium* on woolen cloth treated with differing percentages of soap and oil based on the weight of wool and for the most part in 1 per cent aqueous solution and for different periods of incubation at around 75° F. (25° C.). The data indicate that soap and vegetable oils act to aid the growth of the fungi which he sums up in a sentence which in effect is that soaps, oils, etc., furnish energy and carbon and that wool furnishes nitrogen for the growth. Secretion of enzymes is mentioned in several places as indicating that they enter into the processes of growth but they are not given any detailed consideration such as the author believes they warrant or indeed necessitate if we are to get to the bottom of the problem. The paper closes in a brief discussion of prevention of mildew where it is pointed out that control of moisture, alkalinity and temperature in mill storage are the best precautionary measures but that antiseptics are best when the goods are to be shipped abroad and indicates that sodium silico fluoride is so far the only one that has given any real satisfaction for this purpose.

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[1] L. D. Galloway, "The Formation of 'Diamond-Spot' Stains by Mildew Fungi," *Journal*, Textile Inst., October, 1931.

The author has mentioned that for some reason silk goods are not so much subject to damage from molds as cotton and wool goods and shall leave the subject with that statement, but there is a field of possible practical application of the action of the proteases in silk manufacture that is worthy of further consideration.

Silk-wool unions are common in the industry. The silk in the gum is usually woven with the woolen or worsted yarns which necessitates the removal of the sericin before dyeing. This is usually done in the same way that is used in all-silk goods with the result that there is tendering of the wool yarns and a bleaching operation must be used when light shades are contemplated on account of the yellowish-brown cast given to the wool in the boil-off operation. The action of alkaline detergents on wool has been given attention from time to time for a number of years without careful consideration of the effect of temperature and pH value together and the tendering and browning were not very clearly explained. Mosher[1] has recently undertaken a fairly exhaustive study of the action of some commercial proteases in silk degumming on the assumption that these proteases might accomplish in a short period what had required a comparatively long time and unsanitary conditions in the primitive fermentation processes, and might not prove harmful to wool.

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[1] R. Burgess, "A Contribution to the Microbiology of Wool," *Journal*, Textile Inst., T315 (1928); also "Further Studies on the Microbiology of Wool—The Enhancement of 'Mildew' by Soaps and Vegetable Oils," *Journal*, Textile Inst., T333 (1929).

His first study was on pepsin degumming on which Johnson and Shelton had already made a quite extensive study and established that silk gum was composed of two proteins which they called sericin A and sericin B, the first being easily removed by pepsin digestion while the second was only slowly removed. Hydrochloric acid was used as activator for the pepsin which required degumming effect of the acid. This was found to be less than one per cent below 105° F. (40° C.), but at 120° F. (50° C.) it accounted for 5 per cent of the loss of sericin.

The optimum conditions were found to be: pH value, 1.8; exposure, at least four hours; pepsin concentration, $\frac{1}{4}$ per cent; and temperature, 105° F. (40° C.). Fortunately, the fibroin does not easily break down under these conditions so that the time element does not require careful control. Trypsin in which the activator is alkaline was examined with optimum conditions: pH value, 8.1 most favorable in practice; treated at least eight hours; temperature, 105° F. (40° C.); and trypsin concentration, $\frac{1}{4}$ per cent. The best activator was found to be a combination of $\frac{1}{2}$ per cent sodium bicarbonate and $\frac{1}{20}$ per cent sodium carbonate. Papain, one of the most active proteases and one of possible very low cost, is given careful examination but with negative practical result on account of the chemical character of the only two activators, hydrocyanic and hydrosulfuric acids, that gave high enough activation. Bromelin, a protease from pineapple, was examined and gave very much the same results as papain, being ruled out by the same poisonous activators.

Korofor and Serizyme, two proprietary enzymes of bacterial origin were studied and compared with each other and with other enzymes. The optimum conditions for Korofor were found to be: pH value, between 8 and 9; digested, at least eight hours; temperature 130° F. (54° C.); and concentration of Korofor, 2 per cent. Serizyme gave about the same optimum conditions as Korofor but was found to be more active than Korofor—Korofor discolored silk to some extent but Serizyme did not.

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[1] H. H. Mosher, "Enzymes as Silk Degumming Agents," *American Silk Journal*, August, September and October, 1931.

There was a considerable fraction of the silk gum remaining on the silk in all cases of enzyme degumming examined. No commercially successful way of removing this fraction of the gum was found that would not be somewhat detrimental to wool in silk-wool unions. Further studies of this problem are in progress which may in the near future lead to a commercially successful process for degumming the silk in silk-wool unions without injury to the wool.

The author has shown that enzymes are important factors in some investigations of textile problems that are of immediate economic interest to manufacturers of textile products and has briefly described attempts to find satisfactory solutions of the problems and may have left the impression that these are suggestive of the extent of the type of textile problems that may involve the study of enzymes in order to arrive at any complete understanding of them. I should not like to leave such an impression as I consider the study of enzymes and their actions of much more far-reaching value to textile industries than is indicated by these few problems. For example, improvement in textile raw material, which should always be of active interest to textile manufacturers, involves far-reaching studies of enzymes in the activities in food conversion and absorption, soil fertility, immunity from diseases, etc. A competent investigator for such intricate studies should be acquainted with the problems of the isolation and purification of enzymes and the very intricate procedures that have been used in attempts to control and determine specific enzyme actions in a way that can be formulated and repeated by other workers.

A quick introduction to this training may be obtained by first consulting a variety of modern books of the nature of advanced textbooks such as: Catalysis in Theory and Practice; Colloidal Chemistry; Physiological Chemistry; Microbiology; Bio-chemistry (theoretical and applied); Immuno-Chemistry; Chemistry of Plant Products; Fermentation; and others. All of these will have one or more chapters devoted to enzymes and will furnish many references to the literature of enzymes. Good textbooks entirely devoted to enzymes are available but should not be relied on to furnish all the information needed. A liberal laboratory training should accompany the use of textbooks and takes not weeks and months but years, which suggests that the younger generation of biochemists should be the ones to prepare for such broad investigations in the hope that a few years hence they will be needed in the textile laboratories.

ATMOSPHERIC CONTROL IN THE TEXTILE INDUSTRY

By R. H. Brown[1]

Synopsis

In this paper the general purposes and benefits of controlling atmospheric conditions—particularly relative humidity—in textile mills, are briefly outlined. Among the well recognized advantages are: Improved production, better product, less waste; controlled sizes and weights of yarn and fabrics; better working conditions for the operatives.

Various methods of handling the moisture question in the testing of yarns and fabrics are listed. The standard atmosphere method, which is believed by many to be most suitable for general use, is explained in some detail.

The principal types of apparatus for maintaining and controlling relative humidity are classified. These include direct humidifiers of various sorts suitable for local distribution, and centrally located air conditioning chambers with distributing ducts. The importance of accurate and reliable automatic regulating devices is stressed. Improved methods of computing capacity requirements are contrasted with rule of thumb methods.

Certain special methods and devices for atmospheric control in hot textile departments and testing laboratories and for the conditioning of finished cloth are outlined. These are among the most recent important developments in air conditioning for textile mills.

With few exceptions those engaged in the manufacture, conditioning or testing of yarns and fabrics, of cotton, silk, linen, wool, jute, hemp, rayon—in fact any fibers of either vegetable or animal origin—find it highly desirable and in many cases essential to maintain constant and uniform atmospheric conditions at all times. In particular the control of relative humidity has been found beneficial. Although the extent and precision of such control varies for different materials and processes, the requirements are sufficiently general to make the subject of atmospheric control comparable in importance to the proper selection of processing or testing machinery.

Purposes of Atmospheric Control

Modern methods in textile manufacture which involve rapid manipulation of the fibers call for increased strength, toughness and pliability to prevent breakage of fiber and yarn. Such important considerations as rate of production, quality of the product and economy in raw material are known to be influenced by moisture content. It is a well recognized fact that moisture content, or "regain" in the material varies with the relative humidity (and to a slight extent with the temperature) of the air to which the material is exposed. Consequently control of atmospheric conditions is considered essential to satisfactory and economical manufacture.

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Apart from the actual manipulation of fibers during the manufacturing process, atmospheric control is of recognized importance in the regulation of sizes and weights of textile materials and products. This is readily appreciated when we consider that the normal moisture regain (or percentage of water content compared to oven-dried weight of the material) ranges from as little as 6 per cent to as high as 16 per cent for various textile materials. The regain of any given material exposed to an uncontrolled atmosphere may easily double during the course of a single day as the result of ordinary changes in weather conditions. When goods are bought and sold on the basis of weight, changes in regain result in losses to buyer or seller unless regain is ascertained by test and allowed for in accordance with established standards. Atmospheric control, which serves to bring regain within satisfactory limits prior to weighing tests, is a highly satisfactory method of forestalling such losses.

Another well-established purpose and advantage of atmospheric control in the textile industry is the maintenance of improved conditions from the point of view of the health and comfort of the workers. For most departments and processes, temperatures and humidities most essential to satisfactory and economical manufacture fall within the range of conditions which, though not ideal, are suitable from the health standpoint. In those departments where moderately high or high relative humidities are needed, it usually is not necessary that temperature also be high. Consequently if the method used for maintaining and controlling relative humidity serves simultaneously to keep temperature within satisfactory limits, a double purpose is served by the air conditioning equipment.

Modern methods of humidification differ greatly from old time methods in respect to temperatures maintained. A properly designed system provides for evaporative cooling sufficient to absorb all heat from machinery or other sources liberated within the rooms served. It permits ample ventilation so that continuous evaporation of large quantities of water is possible. As a result, well-humidified spinning and twisting departments, weave rooms, etc., formerly considered to be unbearably hot during the summer season are now maintained as cool as and in many cases cooler than the outdoor air. It would be possible to go further and provide for complete refrigeration of textile mills during the hot season, but the expense of such refrigerating equipment is not ordinarily justified in view of the degree of comfort now attainable with the highly perfected systems which combine high evaporative capacity with controlled ventilation.

In certain special textile processes where low temperatures or low relative humidities are essential regardless of weather conditions, the use of refrigerating equipment is necessary. Improvement in design and reduction in the initial and operating cost of such equipment have lately extended its popularity and usefulness.

METHODS OF TESTING COMPARED

The last few years have witnessed a steady improvement in methods and apparatus used in textile testing. Much of the improvement has been brought about through the activities of this Society. In particular the subject of moisture and its effects on the physical properties of textile materials and products has been carefully studied and all recently drafted test methods include definite specifications regarding moisture or correction for moisture. There are five possible methods for handling the moisture question in the test room, as follows:

1. Test all specimens in the bone dry state and make comparisons on that basis. Except for weight tests, the objection to this method is the practical difficulty of completing tests while samples are bone dry. Also it is contended that results of bone-dry tests for strength, etc., are not a satisfactory index of results which would be obtained under normal conditions.
2. Test specimens in a thoroughly wet condition. This method of test has been used in special tests for strength on account of the comparative ease of preparing specimens. It has merit for routine testing of certain types of goods, particularly rayon, but the assumption should not be made that results of comparative tests on different specimens when wet provide satisfactory data for comparing the same specimens under conditions of normal regain.
3. Test "as is," then measure regain of tested specimens and correct to a standard regain basis. This method involves the use of correction tables for each material and structure, the accuracy of which may be open to question for general use.
4. Test specimens only when regain as ascertained by test falls within certain specified limits for each material. This method involves the establishment of regain standards for a wide variety of materials and structures. Such standards of regain are to some extent arbitrary and invite controversy as to their values and methods of conditioning necessary to secure them.
5. Condition all specimens before testing in a so-called "standard atmosphere" of specified relative humidity and temperature. The object of this method is to bring each specimen before testing into hygroscopic equilibrium with the standard atmospheric condition. The method requires atmospheric control apparatus of a dependable nature which adds to the cost of the laboratory equipment, but which makes for convenience in the testing procedure and

largely eliminates uncertainties and errors in comparative data. The standard atmosphere method has many advocates and is given preference in many existing testing specifications.

STANDARD ATMOSPHERE

As ordinarily defined the standard atmosphere is a condition of 65 per cent relative humidity and 70° F. (21° C.) temperature. Tolerances approved by the Society's Committee D-13 on Textile Materials are plus or minus 1 per cent in relative humidity and plus 10° F. (5.6° C.) in temperature. These tolerances are important in denoting the comparative effect of changes in relative humidity and temperature on regain and the properties of the materials under test. In the case of cotton, for instance, tests have shown that a 10° F. (5.6° C.) rise in temperature (from 70° F. (21° C.) to 80° F. (27° C.)) has approximately the same effect as a 1 per cent drop in relative humidity (from 65 per cent to 64 per cent). In the case of silk and wool the comparative effect of temperature is slightly greater than in the case of cotton. In no ordinary case does a change in temperature of 10° F. (5.6° C.) correspond to a change of more than 2 per cent in relative humidity. For this reason, the specified 70 to 80° F. (21 to 27° C.) temperature range is not excessive in comparison with an allowable range of 66 to 64 per cent in relative humidity—a desirable and practical tolerance.

SPECIAL REQUIREMENTS

The requirements for atmospheric control are so varied that many different types of equipment can be used to advantage in the textile industry. No one type is suitable for all mills and in many two or more types of equipment are sometimes advisable, each serving one or more departments.

In mills where yarns are spun from natural fibers or where woven goods are produced from yarns of either vegetable or animal origin, humidification is the principal requirement. A system of direct humidifying usually is recommended. Close control of relative humidity is needed but temperature may vary within limits representing the range of comfort.

In knitting mills, both humidity and temperature control are desirable and the entire avoidance of free moisture in the room is a wise precaution. Cleansing of outdoor air before admitting it to the mill also is desirable. These are features of the central station system, to which reference will be made later.

The manufacture of rayon and other synthetic fibers involves both temperature and humidity control at levels calling for cooling and dehumidification during most of the year. Dehumidifying equipment also is essential in testing laboratories where both humidity and temperature are constantly maintained within specified limits.

Automatic Airchanger:

The most recent outstanding development in atmospheric control for hot textile mill departments is the automatic airchanger which provides forced ventilation in sufficient quantity to utilize full evaporative capacity of a high capacity humidifying system during summer weather. Under normal conditions when maximum cooling is desired this system keeps the humidifiers in continuous operation and controls ventilation directly from the humidity regulator. This insures maintenance of the desired relative humidity and at the same time provides for the greatest possible reduction in room temperature. In respect to cooling secured, this combined airchanger and humidifying system is fully equal to a central station system using recirculated water and is much less expensive.

Methods of Regulating:

Automatic regulators for starting and stopping humidifiers, for controlling heaters, dampers, ventilating fans, etc., are of three principal types: (1) thermostats, (2) humidity regulators of the wet and dry bulb type or psychrostats, and (3) humidity regulators of the absorption type or hygrostats. In special cases a fourth type, the wet bulb temperature regulator, is used.

Thermostats may control heating, cooling or ventilating equipment. In some cases they may be used to vary the maximum evaporative capacity of humidifiers in accordance with major demand requirements.

The wet and dry bulb humidity regulator or psychrostat is a highly perfected instrument which operates to control relative humidity regardless of temperature by actuation of a humidifier valve or other humidity influencing mechanism. The psychrostat contains two compartments maintained respectively at the dry and wet bulb temperatures of the room air and through which a sample of room air is drawn. Thermostatic metal bellows act differentially through leverage mechanism to close or open an air port, the resulting building up or release of pressure serving to actuate a relay valve which in turn opens or closes a main valve supplying air or water to the humidifiers.

The hygrostat contains a moisture absorptive or hygroscopic material, the elongation or contraction of which, with changes in regain as influenced by atmospheric conditions, acts through suitable pneumatic valve or electric contacts to effect starting or stopping of the humidifiers. Some hygrostats are more sensitive and reliable than others but all are influenced to some extent by temperature—especially sudden changes in temperature—and to aging of the hygroscopic element which should be calibrated frequently and renewed occasionally. Of the various animal and vegetable materials used for this purpose the human hair has been found most reliable and sensitive over long periods of use.

CALCULATIONS

Methods of calculating humidifying and ventilating capacities for textile installations have been highly perfected in recent years. Rules of thumb have been largely discarded in favor of exact mathematical calculations in all cases where thermal data are known or can readily be ascertained. These improved methods of calculation coupled with improved design of the humidifying and automatic regulating equipment have made it possible to secure more satisfactory and stable atmospheric conditions in all mill departments with consequently greater return on the invested capital.

No longer is it satisfactory to install an arbitrary number of units or pounds of water per hour for each unit of volume in a mill and department of stated character. Instead we secure accurate data on the amount of heat to be absorbed (including heat from motors and processing machines, lights, people and from outdoors) at the required atmospheric conditions. With these as a basis, the required evaporative capacity and frequency of air changes are computed. Outdoor conditions against which capacities are desirably figured are ascertained from a summary of Weather Bureau statistics covering a period of many years.

EFFECTIVE TEMPERATURE

In establishing desirable limits of temperature, humidity and air movement from the point of view of comfort and efficiency of the workers, research data on effective temperature published in the *Transactions* of the American Society of Heating and Ventilating Engineers have been used to advantage. These limits have been checked by numerous mill tests. In this connection distinction between ideal and commercial limits of comfort should not be overlooked.

TYPES OF HUMIDIFIERS AND AIR CONDITIONERS

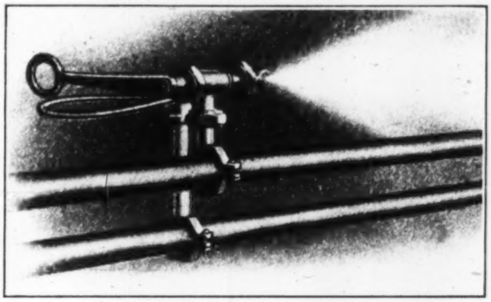
The principal types of equipment suitable for textile mill use will be listed. These include locally distributed humidifiers of various sorts as well as central station systems.

Direct Humidification:

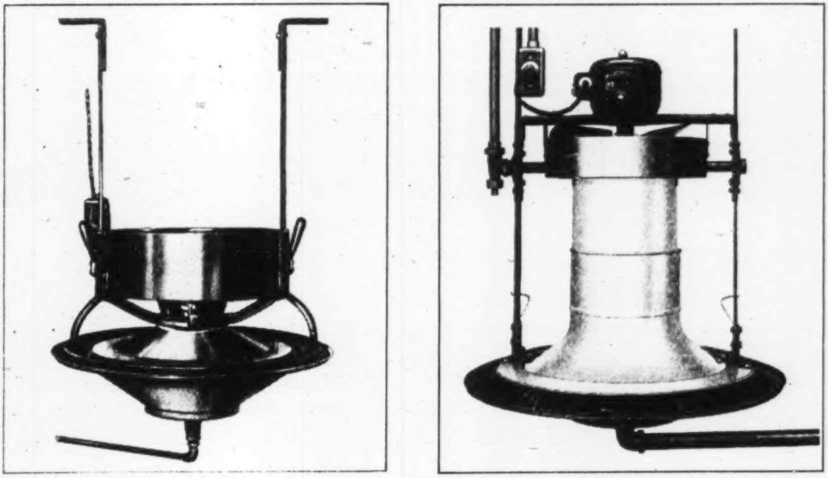
The essentials of a good direct humidifying system are:

1. Adequate total evaporative capacity.

2. Ample number of humidifying units or moisture outlets, so that conditions may be maintained with a close degree of uniformity when the system is operating at either light or peak load.



(*a*) Turbo Atomizer Humidifier.



(*b*) Centrifugal Humidifier. (*c*) High Duty Humidifier.

FIG. 1.—Humidifiers of the Direct Type.

3. Satisfactory performance of each unit. Fixed capacity over a long period without undue accumulations of lint, etc., requiring cleaning. Good quality of spray with absence of coarse particles.

4. Dependable and accurate system of automatic regulation with regulators located in working area of the room at representative points such that conditions can be maintained uniformly without local variations, and constantly regardless of weather changes, starting and stopping of mill machinery, etc.

Humidifiers of the direct type include atomizers, centrifugals and high duty humidifiers. Turbo atomizers (Fig. 1 (*a*)) operate by air under pressure. The jet of air induces a flow of water through an adjoining orifice concentric with the air port. These humidifiers are simple in construction. They deliver a fine spray directly into the room to be humidified. Numerous units of relatively low capacity are advantageously located to provide ample total capacity with uniform distribution of moisture. They can be used satisfactorily in high or low posted rooms and are particularly suitable where belts or other obstructions would interfere with larger types of humidifiers. The performance of atomizers is unaffected by lint, dust or other atmospheric impurities.

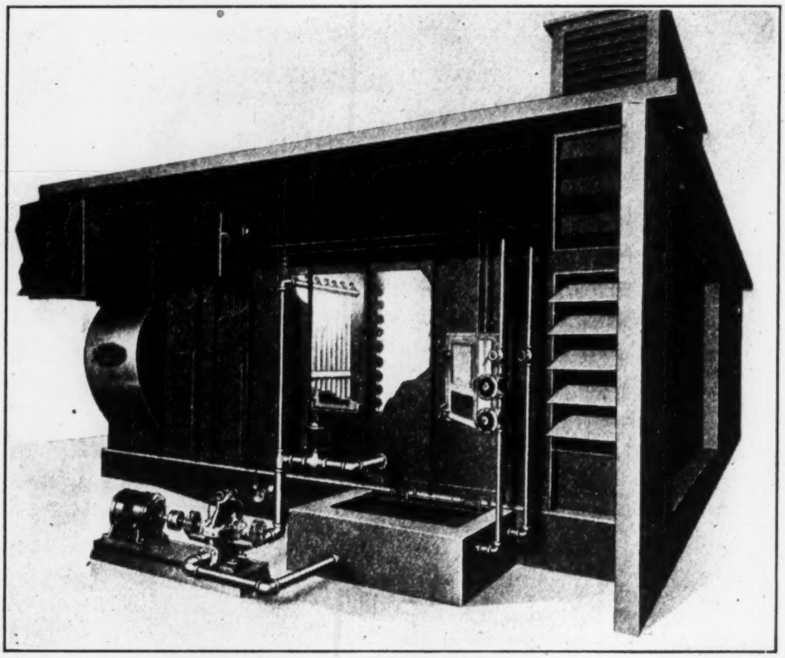


FIG. 2.—Central Station Air Conditioner.

Centrifugal humidifiers (Fig. 1 (*b*)) also are locally distributed. Each consists of a motor-driven disk which causes water supplied at low pressure to be thrown against a series of teeth or corrugations thereby being broken into spray which is discharged into the room by the aid of a fan. When such humidifiers are designed to deliver spray in all directions they have evaporative capacities two or three times as great as atomizers. The performance of centrifugal humidifiers is somewhat affected by lint and dust in the air. Use of such units is ordinarily confined to small installations and where the air is relatively clean.

So-called high duty humidifiers (Fig. 1 (*c*)) operate by water under high pressure. They too are mounted overhead in the room to be humidified. Spray is generated within a casing below which is a pan which catches the unevaporated spray. The unused water is drained to a central filter tank from which it is repumped to the humidifier nozzles. Above each unit is a fan which delivers air partly through the spray and partly down the outside of the casing. The force and proper proportioning of the air currents account for the high evaporative capacity of this type of humidifier—greater than that of any other unit which sprays directly into the room air. The high duty humidifier is capable of satisfactory performance at capacities up to 10 gal. per hour or 5 to 10 times the capacity of humidifiers of the atomizer type. This is the most economical type of humidifier for large installations. It is particularly adaptable to hot spinning and twisting departments where high evaporative cooling is essential to comfort.

Central Stations:

The central station air conditioning system (Fig. 2) consists of a centrally located spray chamber through which air from outdoors or recirculated from the mill is drawn by a large pressure type fan. After being washed and saturated, the air with or without subsequent heating is delivered through a duct system to the room or rooms served. By controlling the volume of air, the temperature of the spray water and degree of heating, any desirable condition of humidity and temperature may be attained. This type of system is essential where complete control of conditions is needed. It can be designed to include any desirable function in atmospheric control. In the textile industry the central station system is particularly adapted to installations which involve close control of temperature as well as relative humidity and especially where exceptional cooling or dehumidification is needed, in which case refrigeration is a necessary adjunct. Automatic regulation may be simple or complicated depending upon the number of rooms to be treated and the required conditions in each.

Small installations of the central station type are useful for controlling atmospheric conditions in "conditioning rooms" where textile yarns or fabrics are treated for short or long periods. A recent development in cloth conditioning which has proved of considerable value in woolen and worsted mills is the application of equipment of the central station type to a chamber through which cloth passes after leaving the hot press and where regain is quickly restored to a normal value. The process is continuous so that no additional time or labor is required. The need of subsequent dewing or other unsatisfactory treatment is entirely avoided. Regain is definitely established which fixes weight and dimensions as well as color shade.

In recent years the use of atmospheric control equipment in textile testing laboratories has steadily increased, with resulting improvement in the accuracy of test data and the elimination of inconsistencies and misunderstandings. Apparatus for controlling relative humidity is simple and not unduly expensive. A system of humidifiers of the turbo atomizer type is satisfactory for the purpose and many well-known laboratories are so equipped. Automatic regulators of the psychrometric wet and dry bulb type are preferable to the hygroscopic on account of the unavoidable variations in temperature during summer weather and the need of careful and frequent checking and readjustment. Hygroscopic regulators which lack extreme sensitivity are especially undesirable for the purpose.

Small enclosed cabinets wherein samples to be tested are conditioned to specified atmospheric conditions have been used with some degree of success. Such cabinets sometimes contain the testing machines which are operated from without by hands inserted in air-tight rubber sleeves and gloves. While devices of this character are undoubtedly suitable for special work, the advantages of conditioning the test room as a whole so that numerous large samples may be suspended on revolving reels and the tester may conduct a variety of tests under the same atmospheric conditions are obvious. The cost of conditioning a whole room usually is no greater than for a small cabinet.

Recent improvements in apparatus of the central station type suitable for the conditioning of textile testing laboratories have resulted in a rapidly increasing number of such installations. Whereas an automatically regulated atomizer system may be preferable to a central station system without refrigeration, complete air conditioning with refrigeration makes an ideal installation for combined humidity and temperature control. Constant and accurate regulation of conditions in the test room has advantages which are considered by many to justify fully the added expense of the complete system. With such a system tests may be made on hot humid summer days when frequently it would be impossible without refrigerating equipment to maintain atmospheric conditions corresponding to A.S.T.M. or Government standards.

ASBESTOS TEXTILES

BY C. K. DILLINGHAM[1]

SYNOPSIS

This paper on asbestos textiles is a brief description of the occurrence and mining of asbestos fiber, its subsequent manufacture into asbestos textiles, and a brief outline of their characteristics and uses. No attempt has been made to go into technical details, but rather to present to those not familiar with the product a brief comparison between asbestos and other familiar textile fibers.

Asbestos, that remarkable mineral born millions of years ago in the volcanic fires of Earth's creation and formed under the terrific pressures that were set up as the crust of our planet began to cool off, has, as you all know, scores and hundreds of uses. Perhaps one of its most interesting adaptations has been its manufacture into asbestos textiles.

It is not commonly known that the use of asbestos textiles dates far back into ancient times. It was originally known as amianthus cloth and was used by the ancient Greeks and Romans to wrap dead bodies, placed on the funeral pyre, in order to preserve the ashes of the body. It was referred to in many an ancient document as a rare and costly cloth, the funeral dress of kings. Marco Polo, in the thirteenth Century, while traveling in Siberia, was shown cloth made from asbestos which the natives pointed to in wonder because it withstood the action of fire. Plutarch writes of his "perpetual lamp wick" made from Carpathian linen or asbestos.

Because of its ancient and modern place in the textile field, I believe some facts regarding asbestos and its adaptation in textile work will be of unusual interest. While asbestos in various forms occurs in all parts of the world, the general types in which textile manufacturers are interested are three in number, namely, chrysotile, represented by Canadian, Russian, and some kinds of African; the iron free, also chrysotile, represented by Arizona, Australian and one type of African; and the African brown and blue acid-resisting fibers. As Canadian asbestos is truly representative of the largest group and is probably the most widely known, this paper, because of its limited scope, should be considered as dealing only with Canadian chrysotile asbestos unless otherwise noted.

The asbestos fiber occurs as veins in serpentine rock, varying in width from almost nothing up to a rare maximum of 6 in. The fibers run across the vein so that the width of the vein is the length of fiber. Asbestos mining is in most cases really asbestos quarrying, as blasting is resorted to in order to loosen masses of rock in open pits after which the fiber is removed from the rock in varying ratios of about one ton of fiber to fifteen or twenty tons of material.

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As soon as the blast has settled, the grading of the asbestos fiber begins. It is first divided into two main divisions, crude and mill fibers. The crude fiber is obtained by collecting the larger pieces of fiber shaken loose by the blast, and removing by hand the rock still clinging to it. It is then still further sorted according to length, but not with the degree of accuracy that is customary in the grading of cotton and wool, and is then packed in burlap bags and shipped to the point of consumption. The rest of the rock is then put through the mill at the mine, the rock crushed off, the fiber worked into a soft matted mass, screened, graded and packed as mill or milled fibers.

It is extremely difficult to grade or evaluate asbestos fiber as, with the exception of crude fiber, it is impossible to measure its length, and even if it were possible, the length of the fiber would not tell the story. In order, however, that there may be some specification or standard applicable to the many grades of mill fiber, the various asbestos mines have adopted a standard screen test by which mill fiber is classified into its many grades. The standard equipment consists of three screens and a pan placed one on top the other. The top screen is ½-in. mesh, the second screen is No. 4 mesh, the third screen is No. 10 mesh, with the pan at the bottom. A pound of fiber is placed on the top screen, and the apparatus is shaken by a cam having 600 revolutions in 2 minutes. After the 2-minute shaking, the amounts of fiber remaining on each screen and in the pan are carefully weighed, and the results given in ounces. Thus a fiber which is classified as a 2-8-4-2 fiber means that, after this shaking test, 2 oz. of fiber will remain on the top screen, 8 oz. on the second, 4 oz. on the third, and 2 oz. in the pan. While the results obtained by this method show considerable variation, it is a roughly accurate method of grading fiber. In the lower grades it determines the value of the fiber more or less accurately, as it does indicate its cleanliness, but in the higher grades, it takes no account of a quality of asbestos which is extremely important in textiles, packings, filter fibers, and possibly high-grade papers and insulations, namely, the natural life and resiliency of the fiber itself. Therefore, in the selection of fibers for textile purposes, to all the mechanical quality tests must be added knowledge of the workability of the different asbestos fibers obtained only through long experience.

In general we may say that the various grades of crude fibers and the two or three top grades of mill fibers can be used for the production of asbestos textiles. Some asbestos yarns require all crude fiber, due to the severe service to which they are put, others are made from a mixture of crude and mill fibers, while some of the cheaper grades of yarn and wick can be produced almost entirely from mill fiber. When crude fiber is used, the lumps of fiber as received from the mine are crushed and freed from all remaining rock. It is then passed through a willow which in general consists of two revolving beaters for the purpose of opening and fluffing up the fibers. As the mill fiber needs no further crushing, it is usually only fed through the willow. If crude and mill fiber are used they are usually mixed at the willow.

The next operation in the production of asbestos textiles is the mixing picker, and it is at this point that the grade or quality of the yarn is determined by the mixture of a certain quantity of vegetable fiber, usually cotton, with the asbestos. Cotton is used to reduce the cost of asbestos yarn to commercial limits. Its great carrying power makes it possible to produce a stronger asbestos yarn from lower-grade asbestos or from a higher-grade asbestos with less waste than without it, and as there is very little necessity for an all-asbestos yarn, varying amounts of cotton will be found in practically 98 per cent of asbestos textiles. The mixing picker used in asbestos is usually of the heavy Fearnaught type quite unlike the cotton picker or lapper.

In carding, spinning and twisting asbestos yarns special equipment of heavier, more rugged construction must be used than in the case of other textile fibers, but in designs and methods asbestos machines more nearly follow the woolen system than any other. It is quite common in the industry to use a breaker and finisher card hooked together by means of a so-called camel-back feed. The asbestos and cotton mixture is delivered to the breaker card by means of a feed box, automatically weighing out a predetermined amount of mix at set intervals. Asbestos roving without twist is commonly taken from the finisher card by means of a ring doffer, wipe roll and rub motion, although in the case of some of the finer yarns tape condensers replace the ring doffer and wipe roll.

The asbestos roving delivered by the card is spun into yarn by two methods, namely, mule and ring, both producing yarn by the same principle, that is by twisting the soft roving on its own axis, thereby binding the fibrous mass into a strong compact thread, where formerly it had very little cohesive strength. In the main, mule spinning is used to produce a softer, more pliable single yarn to be later twisted into a plied yarn while ring spinning is used to produce a harder twisted stronger yarn which can be used in the single on braiders and winders in packings, and in the weaving of fine cloths and tapes. Draft as understood in cotton spinning is not used.

The spun yarn is spooled up and prepared for the twister in the same manner as is commonly found in the manufacturing processes of other textile fibers. An asbestos yarn twister, with the exception of its size and weight, is of the same general type as used in cotton and wool. Asbestos yarns are twisted into ply yarns in the same manner as other yarns, with the addition that a large amount of asbestos yarn has one or more strands of brass or copper wire twisted with a varying number of asbestos plies into what is known as wire-inserted asbestos yarn or asbestos metallic yarn. The name wire inserted yarn is derived from the fact that wire strands tend to twist towards the center of the yarn.

Asbestos yarns and roving are produced and sold by size or cut and not by diameter. The size or cut of the yarn means the number of 100 yd. to the pound of the single- or one-ply yarn. Thus a 10-cut yarn or roving will average 1000 yd. per pound. Although asbestos has been spun into yarns as fine as 70's the commercial sizes run from 8's to 20's, as there is very little call for the higher counts. With a few exceptions the count or cut jumps 200 yd. at a time as for example 8's, 10's and 12's, because asbestos yarn due to its mineral raw material is recognized as varying considerably in yardage. Tolerances for 14's and finer are accepted as being ± 100 yd., from the count and ± 50 yd., for lower counts. It would therefore be rather difficult to determine intermediate cuts or counts as their yardages would at times overlap.

As ply yarns are made by twisting together two or more strands of single yarn whose yardage has already been determined, it is evident that the yardage of a ply yarn will be the yardage of the single yarn divided by the number of plies, less a certain amount for the contraction caused by the twist. Thus a 10-cut 2-ply yarn would have a yardage of 1000 divided by 2 less 40 or approximately 460. As a rule, the yardage of a 2-ply yarn is about 46 per cent of the single ply. If wire is inserted in the yarn its weight also reduces the yardage of the ply yarn, as here again the size of the single-ply asbestos yarn is the governing factor. A wire-inserted asbestos yarn containing three plies of 10-cut yarn and 2 wires is known as a 10-cut 3-ply wire-inserted yarn and can be written as 10/3 and 2, or in common mill parlance 1032. If the asbestos strands are 10-cut yarn and no other specifications as to size and percentage of wire or weight of finished yarn have been especially agreed upon, the mill has made a good delivery.

The five generally recognized qualities or grades of asbestos yarns are outlined in the Society's proposed revised Specifications for Tolerances and Test Methods for Asbestos Yarn (D 299 - 29)[1] as follows: Grade A-1, a minimum of 77 per cent asbestos; grade A, 80 to 85 per cent; grade AA, 90 to 92 per cent; grade AAA, 95 to 96 per cent; and grade AAAA, all asbestos with a trace usually about 1 per cent of foreign matter permitted. These grades are the result of years of experience in producing asbestos textile to meet all requirements of industry as cheaply as possible, and in addition to covering all necessary qualities enable the manufacturers to utilize in the lowest grades a part of the waste produced in the higher grades. The grade or quality of a wire-inserted asbestos yarn is determined by the grade of the asbestos strands in the yarn, no account whatever being taken of the wire. All tests are made with the wire removed.

A visitor to the weaving room of an asbestos textile mill would probably see the greatest collection of equipment ever brought together in a single textile department. Here asbestos textile fabrics are woven in widths varying from $\frac{1}{2}$ to 124 in., in thicknesses from 0.015 to more than 1 in., in textures from 6 ends per inch to more than 100, and in weights from $\frac{1}{2}$ lb. per sq. yd. to 6 lb. per sq. ft. For cloths, various of the common types of fly shuttle looms are used together with some special looms of heavier construction. Asbestos brake linings and asbestos tapes are woven on multiple-shuttle, narrow-fabric looms. Both creel and beam weaving are employed depending on circumstances. In cloths the plain and common twill weaves are the most usual while in brake linings various ply weaves are used. All sizes and grades of asbestos yarns are woven into fabrics.

Asbestos is commonly called fireproof, but a better term would be fire resistant. A sufficiently high temperature can eventually destroy almost everything known and asbestos is no exception. The breakdown of asbestos under heat depends entirely upon the loss of its water of hydration, of which chrysotile asbestos has an average of 14 per cent. The water of hydration begins to leave asbestos just above 600° F. (315° C.) but only at a very slow rate. At 1000° F. (540° C.) about one-fourth of it has been driven off, but at this point it begins to go more rapidly so that above 1200° F. (650° C.) it will quickly disappear entirely. After the water of hydration has been driven off the fiber becomes completely calcined and can be crushed to a powder. The length of time during which the fiber is subjected to a given temperature has very little effect, the temperature itself being the important factor.

Asbestos has also been called an insulator against heat. This is also slightly erroneous. Asbestos in solid form is not an insulator but will transmit heat. When woven into a fabric its insulating qualities are almost negligible if applied directly to the source of heat. As an example, a piece of asbestos cloth laid on a metal plate having a temperature of 900° F. (480° C.) reduced the temperature above the cloth only 35° F. (19° C.). However asbestos in cloth or other forms does furnish a strong heat-resisting medium around which insulation in the form of enclosed air spaces, for instance, can be built.

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[1] *Proceedings*, Am. Soc. Testing Mats., Vol. 32, Part I, p. 492 (1932).

In order to give the reader some idea of the temperatures which the various grades of asbestos textiles will safely stand, the following may be stated as a general rule: grade A-1 and grade A, 350 to 400° F. (175 to 205° C.); grade AA, 600° F. (315° C.); grade AAA, 850° F. (455° C.); and grade AAAA, 950° F. (510° C.). These figures must be considered as applying to plain asbestos yarns and cloths without impregnation coating, or treatment of any kind. Special severe conditions may reduce these limits, and, reversely, ideal conditions of service may greatly increase them.

Reference was made previously to iron-free and acid-resisting asbestos fibers. In most chrysotile asbestos, iron is found in both ferrous oxide Fe_20_3 and free magnetic iron Fe_30_4. In some cases where asbestos is used as an insulting wall on electrical wires, the free magnetic iron is objectionable, and for this work a fiber, such as Arizona, Australian, and one type of African, which is free from this form of iron, must be used.

With the exception of the brown and blue African fibers, asbestos is attacked by acids in about the same degree as cotton fibers. From a commercial standpoint weak acids seem to have more effect on the fiber than concentrated acids, except under boiling temperatures, where the action is much increased. In strong hot acid solutions chrysotile asbestos will lose over 50 per cent of its weight. Blue African asbestos stands supreme in acid resistance with a maximum loss of approximately 20 per cent, and the brown African amosite ranks second. Alkalies at ordinary temperatures, up to 20-per-cent strength, have no effect on asbestos, and very little effect beyond that.

The chief outlet for asbestos textiles today is as the raw material for the manufacture of other products such as brake linings and packings, but there is an ever-growing market for asbestos yarns, cloths, and tapes in their primary form to be found in their use on insulated wires, gloves, clothing, theatre curtains, filters, conveyor belts, etc. In fact, wherever a soft, pliable, yet strong, heat-resisting medium is needed there is a market for asbestos textiles.

For centuries asbestos was but a curiosity, a mystic mineral. Today, with its possibilities for being spun, woven, felted or molded into useful form, it is a recognized necessity in our modern-day world.

SOME ASPECTS OF THE STRUCTURE AND PROPERTIES OF THE RAYONS

By Harold De Witt Smith[1]

Synopsis

All of the present-day rayons are made from cellulose. In three of the four commercially successful processes the finished product is highly purified cellulose, the fourth type is a derivative of cellulose. Cellulose is a carbohydrate with three available alcoholic hydroxyl groups. Chemical and physical research have indicated that it has no definite molecular weight. It is built up from ring-shaped glucose residues joined to one another by oxygen bridge to form long chains or "thread molecules." These are grouped parallel to one another into long slim bundles or micellae, these micellae into larger bundles and so on up to the physical boundaries of the visible fibers of cotton, wood or other native cellulosic material. In the manufacture of rayon this orderly structure is broken down and the coagulated filament is composed of a more or less heterogeneous matted mass of micellae and micellar fragments. The degree of orientation of these particles can be controlled to a considerable extent by the method of spinning.

As a result of this micellar structure the degree to which these rod-like particles are oriented within the rayon filament is an index to its behavior. Since the strength of such a structure depends upon the mutual cohesion between the micellae and this in turn upon the area of mutual contact between them, increasing orientation increases the strength. This is accomplished however, at a sacrifice of the elongation. The plastic flow exhibited by all rayons under constant loads is brought to a halt by the increasing intermicellar attraction as the orientation of the flowing micellae improves. The "relaxation" of rayon filaments at a constant extension also alters the orientation and hence the rigidity of the filament.

Cellulose is a very hygroscopic material. The behavior of rayon is very sensitive to changes in amount of absorbed moisture. The absorbed moisture pries the micellae farther apart and acts as an internal lubricant. Hence the cohesive forces are decreased and the deformations and orientations due to the application of external forces proceed more readily.

Attention is also called to the effect of the micellar structure and of the swelling due to moisture absorption on the behavior of the rayons with respect to chemicals and dyes.

Introduction

The Subcommittee on Rayon of the Society's Committee D-13 on Textile Materials first undertook the preparation of a specification for tolerances and test methods for rayon in 1926. This specification is still continued as tentative because of the need for revision from time to time occasioned by the actively developing rayon industry. It provided the first published standard in this country, if not in the world, for a general testing procedure acceptable to both producers and consumers of rayon and for tolerances for some of the physical properties of this material. The specification is in four parts—definitions, identification, tolerances, and test methods.

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[1] A. M. Tenney Associates, New York City.

The aim of this paper is briefly to review the types of rayon as defined in the Society's rayon specifications and then to offer a concise survey of the knowledge of their internal structure, which world-wide research has recently provided, and to examine the relationship of this structure to some of the properties and characteristics which must be considered in drawing up and in revising rayon specifications as well as in the successful utilization of rayon in the textile mill.

WHAT IS RAYON

The Federal Trade Commission adopted the word "rayon" to replace the words "artificial silk." This Society has defined rayon as follows: "A generic term for filaments made from various solutions of modified cellulose by pressing or drawing the cellulose solution through an orifice and solidifying it in the form of a filament or filaments by means of some precipitating medium."

This definition embodies the fundamental fact that all of the present commercial methods of producing rayon utilize cellulose as the raw material. The rayon industry is still wholly a cellulose industry despite constant efforts to manufacture filaments from other raw materials such as silk waste, gelatine, chitin and other substances.

Historically, the birth of the rayon idea appears to have been the suggestion by Robert Hooke, in 1665, of "the possibility of spinning a Kind of Artificial Silk out of some glutinous substance that may equal Natural Silk."

After some two hundred years of rather primitive and desultory efforts by various investigators to imitate the silk worm, Count Chardonnet, who had made a careful study of sericulture in China and Japan, achieved, in 1884, a failure which was really a success. He digested mulberry leaves in nitric acid and succeeded in spinning a solution of the resultant mass in organic solvents into silk-like filaments. But although they were nitrogenous, they were chemically quite unlike silk, which is a protein or animal substance. They were in fact a derivative of cellulose and hence chemically more like vegetable than like animal fibers. Realizing this, he turned, naturally, to cotton, a cheaper and better source of cellulose than mulberry leaves. By 1890 he had learned how to denitrate his filaments, thus reducing their flammability and improving their textile and dyeing properties.

During the next fifteen years other methods of getting cellulose into solution were developed and out of this pioneering work have grown the four present commercial processes whose nature is indicated by the following definitions from the Society's rayon specifications.

"*Nitro-Cellulose Rayon* (Chardonnet).—Filaments composed of a regenerated or denitrated cellulose which has been coagulated or solidified from a solution of nitrated cellulose." The nitrated cotton is dissolved in an ether-alcohol mixture and extruded through fine holes into warm air. The resulting filaments, after subsequent denitration, are composed of cellulose in a very pure form.

"*Viscose Rayon.*—Filaments composed of a regenerated cellulose which has been coagulated or solidified from a solution of cellulose xanthate." The xanthate is produced by treating mercerized cotton or wood pulp with carbon bisulfide. It is soluble in water and is extruded into an acid bath which coagulates the filaments. Subsequent treatment includes desulfurizing, bleaching and washing. The resulting filaments are composed of pure regenerated cellulose.

"*Cuprammonium Rayon.*—Filaments composed of a regenerated cellulose which has been coagulated or solidified from a solution of cellulose in ammoniacal copper oxide." This solvent disperses cellulose directly to an aqueous solution. It may be spun into water or into acid or alkaline baths and is particularly amenable to stretching while in a semiplastic state, with effects to be discussed later.

"*Cellulose Acetate Rayon.*—Filaments composed of an acetic ester of cellulose which has been coagulated or solidified from its solution." The ester is made by treating cotton with acetic anhydride dissolved in acetic acid in the presence of a catalyzer such as sulfuric acid. By subsequent partial hydrolysis, a cellulose acetate is obtained which is soluble in acetone. This solution is spun into warm air and the resulting filaments of cellulose acetate are ready for use, except for subsequent textile processing such as twisting and winding.

The difficulty of identifying with certainty the type of a given sample of rayon is evident from the fact that three of the four types consist in their finished state of a very pure form of cellulose. Identification of the cellulose acetate type is of course simple because its chemical behavior is distinctive from the others. The scheme of identification of the three others, adopted in the rayon specification, depends upon the presence of minute amounts of impurities which are characteristic of the manufacturing process, for instance, nitrogen in the case of the nitrocellulose type and sulfur in the case of the viscose type. Because of improvements in the manufacturing processes, however, and the consequent reduction of these residual impurities, the reliability of such methods may be affected. Hence, the necessity of revision of the standards from time to time to meet the new conditions by embodying the best of such new methods as are worked out by the members of the Society and by other interested bodies who are working along similar lines.

THE STRUCTURE OF RAYON FILAMENTS

Included in the avowed purpose of the Society, namely, "The promotion of knowledge of the materials of engineering and the standardization of specifications and the methods of testing," is the obvious but vital realization that sound standards and specifications must be based on a fundamental understanding of the nature and structure of the material in question.

Here then is a summary, or better, a "synthesis" of some of that "knowledge of the material" which persistent, world-wide research on cellulose in general and on rayon in particular has provided for the benefit of all to whom, like the rayon subcommittee, it may be of interest and of importance.

Structure of Native Cellulose:

Ultimate analysis of purified cellulose indicates the presence of carbon, hydrogen, and oxygen in the ratio $C_6H_{10}O_5$. Chemical research has yielded among many interesting facts, three which have been very helpful in revealing its structure. (1) it is a carbohydrate and can be broken down by hydrolysis (the addition of hydrogen and oxygen in the proportion in which they are present in water) to a sugar, glucose ($C_6H_{12}O_6$) whose yield under proper conditions of hydrolysis is practically quantitative; (2) it has three available hydroxyl groups per $C_6H_{10}O_5$ and consequently behaves like an alcohol with respect to many acids, forming esters as high as the triester with acids, such as the nitrate, acetate and in fact a great number of organic acids; (3) these three hydroxyl groups are attached to particular carbon atoms, namely, the second, third and sixth when numbered according to the order usually employed in writing the structural formula. By repeated methylation followed by hydrolysis, a quantitative yield of 2–3–6 trimethyl glucose can be obtained.

Chemical research on glucose has resulted in the acceptance of a structural formula for one form, known as beta-glucose, in which five of the carbon atoms and one oxygen form a six-atom ring to which the remaining atoms in the glucose molecule are attached as branches. By the removal of the equivalent of one molecule of water, namely, one hydrogen atom from one side of this ring and one hydroxyl group from the other side, these glucose residues may be joined by the chemical bonds of the oxygen bridges between them to form long chain structures. Each succeeding glucose ring in the chain is rotated through 180 deg. about the chain axis so that alternate rings are "face up" and those between them "face down."

Physical research on cellulose fibers, principally by means of X-ray diffraction photographs, confirms this structure. In addition to revealing that the atoms and atomic groups in cellulose are arranged with such regularity that the internal structure of the fibers is decidedly crystalline, this modern research tool has provided accurate information as to the distances between atoms in various configurations, such as C-C, C=O, C-O and O-H.

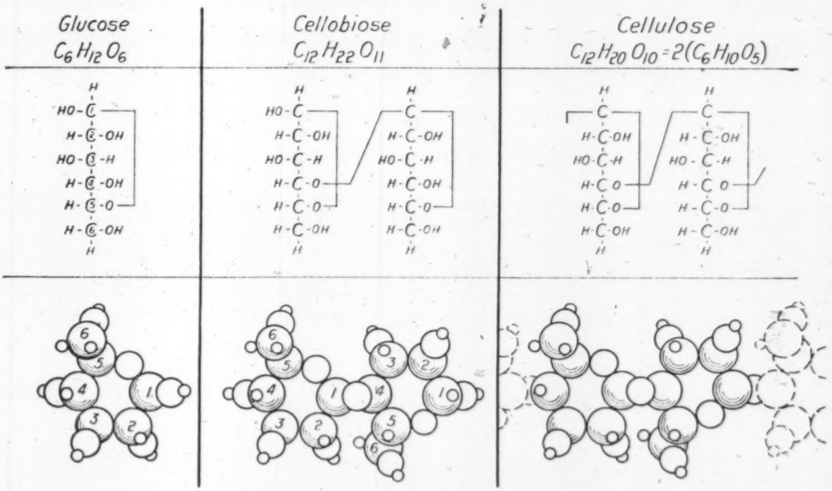

FIG. 1.—Empirical and Structural Formulas and Space Models of Glucose, Cellobiose, Cellulose.

Space models according to K. H. Meyer, *Kolloid Zeitschrift*, Vol. 53, p. 8 (1930).

The combination of these crystallographic dimensional data, the space relationships and dimensions of the cellulose unit cell as revealed by the X-ray, and the known chemical behavior has confirmed this chain structure as outlined above as the one which best fits the properties and behavior of cellulose. Figure 1 gives the empirical and the structural formulas of glucose and cellulose as well as sketches of the space models which visualize the atomic configuration much more clearly than any word description. The large spheres are carbon; the medium spheres, oxygen; and the small spheres hydrogen atoms.

Cellobiose, which appears in the figure, is an intermediate product in the hydrolysis of cellulose to glucose. It does not occur in Nature.

It is included because it is so frequently mentioned in the literature on cellulose structure. Hydrolysis readily breaks down the cellulose into cellobiose and finally glucose. The synthesis of glucose into cellulose, however, has remained until recently an exclusive process of Nature accomplished in the green parts of living plants under the influence of sunlight. In fact, Nature starts with carbon dioxide gas and water and builds these up into glucose, starch and cellulose. An account of the synthesis of glucose from carbon dioxide and water by an English chemist has recently failed of confirmation by others who have attempted to duplicate his reported results by following his directions.

A recent announcement from McGill University of the synthesis of cellulose membranes from glucose by means of enzymes, however, may be the first step in wresting from Nature one more of her secrets. Nevertheless, for the present, and one may safely say for a considerable future, rayon will be made from the bountiful store of natural cellulose and not from gas and water as some of our over-optimistic newspaper friends announced in headlines at the time.

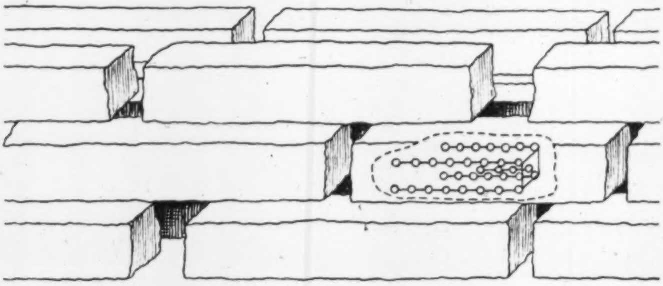

FIG. 2.—Schematic Diagram of Arrangement of Micellae in Ramie Fiber.
According to K. H. Meyer, *Kolloid Zeitschrift*, Vol. 53, p. 8 (1930).

The X-ray diffraction diagrams tell us more. These long chains, comprising in native cellulose some 100 to 120 glucose residues, cling together parallel to one another in bundles of some 50 to 60 chains. These bundles are called micellae, and the above dimensions are, of course, averages. Individual micellae undoubtedly vary greatly in size. The important fact is, however, that they are submicroscopic, long, rod-like particles whose lengths (500 to 600 Ångstrom units[1]) are about ten times their diameters.

In the native fibers, these micellae are packed in parallel to one another somewhat like the bricks in a wall, as illustrated diagrammatically in Fig. 2. This of course is schematic and is undoubtedly far more symmetrical and uniform than the most perfect structure found in Nature. In fact it appears that what was formerly considered an amorphous phase or an adhesive material between the oriented micellae, is actually simply a part of the micellae which are less oriented than the ones which give the crystalline points in the X-ray diagrams. In one micella in the figure the individual glucose residues and chains are indicated.

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[1] One Ångstrom unit equals 0.0000001 mm.

In ramie, the micellae lie straight with their long axes parallel to one another and to the fiber axis. In cotton and wood cellulose, the long axes of the micellae are parallel to one another but they spiral about the fibre axis in concentric layers, one layer to the right, the next layer to the left. This gives a greater flexibility to the structure which is reflected in the comparative properties of the respective fibers.

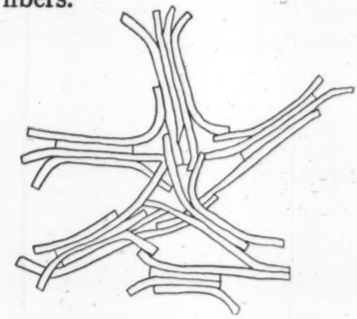

FIG. 3.—Micellar Structure, Unoriented.

According to Bayerl and Roos, *Kunstseide*, Vol. 12, No. 11 (1930).

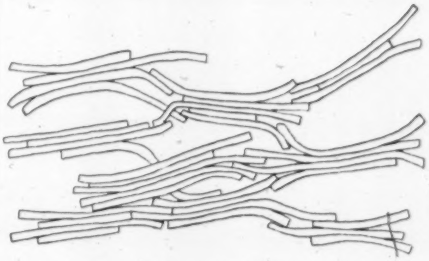

FIG. 4.—Micellar Structure Orientated by Stretching

Ultramicroscopic and microscopic examination of natural cellulose fibers indicates that this principle of long slim particles or bundles is repeated again and again in building up the fiber. Such names as supermicellae, fibrillae and striae have been applied to the observed elements of increasing size of which the native fibers are composed. Not only cellulose but all of the fibrous structures found in Nature including all of the textile fibers appear to be built up in this manner of bundles of long units, rather well oriented with respect to one another, these bundles forming larger bundles also in orderly arrangement, and these again forming larger bundles until we have reached the physical boundaries of the visible fiber itself, be it cotton or wood cellulose or other fibrous substance.

Spinning Solutions:

What happens now when we disperse this neat cellulose structure by preparing a spinning solution for rayon manufacture? No matter which process we use, the bundles are split apart and reduced in size down to colloidal dimensions. Because the primary chemical bonds holding the glucose residues together in a chain are relatively strong, the splitting up seems to be chiefly longitudinal and results in a heterogeneous mass of micellae and micellae fragments dispersed with little or no orientation throughout the solvent medium. Actual measurements of particle size have indicated the presence of particles as fine as single chains. Much of the technique of dispersion and aging of the material during the manufacture of rayon is of course concerned with the control of the size and uniformity of the cellulose particles.

Rayon Structure:

When the spinning solution, or "dope" as it is commonly called, is forced through the fine holes in the spinnerette into the coagulating medium a considerable amount of "recrystallization" or reformation into micellae occurs. The arrangement of the micellae in the newly formed rayon filaments depends largely on the method of spinning. At one extreme is the old method of spinning the viscose type with little or no stretch; that is, the filaments are drawn off at a speed which is only slightly greater than the speed of extrusion from the spinnerette. In such a rayon, the X-ray reveals that the micellae lie in a matted mass like the criss-cross arrangement of fibers in a felt. This is schematically represented in Fig. 3.

TABLE I.—RELATION OF ORIENTATION TO STRENGTH ACCORDING TO CLARK.

TYPE OF RAYON	ORIENTATION	STRENGTH, G. PER DENIER
Ordinary viscose	Moderate	1.51
Viscose sewing rayon	Very good	2.69
New viscose rayon	Very good	2.74
New viscose rayon	Very good	3.77
Lilienfeld	Excellent	4.12
Real Silk	Excellent	2.94

At the other extreme is the stretch spinning of Lilienfeld viscose yarn or of the cuprammonium yarns in which the filaments, while still in a partially coagulated state, are subjected to considerable draft or stretching by reeling them up much more rapidly than they are extruded. The effect of this stretching of the plastic mass is to pull the micellae into line in the direction of the filament axis with consequent increased orientation, as indicated in Fig. 4.

No matter what the process of dispersion or the method of spinning, the final structure of the rayon filament thus resembles that of the native fibers in that it is composed of a mass of long slim particles or micellae, but differs from the natural fibers in that the micellae are smaller and less regular in size and form a more imperfectly arranged network. Most of the differences between the properties of natural fibers and of rayons as well as the distinctive behaviors of the several types of rayon are intimately connected with the orientation of the micellar structure.

THE RELATION BETWEEN MICELLAR STRUCTURE AND PROPERTIES OF THE RAYONS

Effect of Orientation on Strength and Elongation:

While the exact nature of, and differences between the several forces holding together the elements of such a structure are not too clearly understood as yet, it is quite certain that of the three bonds, namely, the longitudinal bond between the glucose residues in a chain, the lateral bond between the chains in a micella and the lateral bond between the micellae, the latter is the weakest. Hence the strength of a cellulosic fiber or filament is determined by the strength of the inter-micellar attraction and this in turn is proportional to the area of mutual contact between micellae. This explains one of the fundamental precepts in the art of spinning rayon, namely, that while we can control the spinning of any given type with respect to either strength or elongation, we cannot control both of these factors arbitrarily beyond certain narrow limits. The more perfect the orientation of the micellae the greater is the strength because of the increased area of contact between them, but the lower is the elongation because the "slack" due to the criss-cross orientation has already been taken up.

The relationship between orientation and strength is indicated by Table I which was compiled by Clark. It should be noted, however, strength alone is no criterion of excellence. It is in fact quite possible for a rayon to be too strong to be good for textile purposes because of concurrent insufficient elongation. The excellence of a rayon, as of any textile yarn, is determined by the perfection of the balance between strength, elongation and other characteristics, and this proper relationship between the several properties is far more important than the absolute value of any one. At this point it should also be made clear that the degree of orientation is of itself in no sense an index of quality, it is merely an index of behavior because of the fact that the internal structure is micellar in nature.

Effect of Orientation on Plastic Flow:

Within the range of small elongations, rayon filaments are truly elastic and obey Hooke's law when loaded and unloaded rapidly. If a small load be hung on a rayon filament or yarn, however, it causes first an immediate extension proportionate to the load, but this is followed by a further increase in length under the constant load at an ever decreasing rate until the rayon finally attains equilibrium again. Thus, while it exhibits a plasticity which is somewhat analogous to viscous flow, it differs from an ideal plastic body which would continue to flow under a constant load at a constant rate to the point of rupture. This hardening effect which rayon exhibits is undoubtedly due to the fact that the micellae tend to become more oriented by the flow or stretching of the filament and the consequent increasing mutual attraction between them acts as a brake which finally counterbalances the load and so brings the flow to a halt. When the load is removed, the filament makes an immediate partial recovery and then creeps back slowly toward its original length which it will eventually reach provided the elastic limit has not been exceeded.

"Relaxation" and Rigidity:

A corollary of this phenomenon which is called "elastic aftereffect," and is present in metals also to a lesser degree, is an equally important effect known as "relaxation." If a filament be subjected to a small extension and held at exactly this extension the internal stress set up will gradually diminish with time. There is apparently a change in the internal structure in the direction of better orientation and such a fiber will not recover its original length until immersed in water which swells it and restores the original orientation.

This phenomenon is of profound practical import in fabric manufacture because it is directly connected with many cases of shiners and streaks in warp or filling. The change in orientation, due to relaxation, even at small extensions causes a change in the rigidity of the filament and hence a yarn which has been stretched slightly and held in this stretched condition will bend or crimp differently than its neighbors in the formation of the weave and hence cause a difference in light reflection which appears as a shiner or a streak. This may not show up until the fabric has been finished since, when wetted out, the "relaxed" yarn will contract more than its neighbors, thus intensifying the difference in crimp.

Increasing orientation and increasing rigidity go hand in hand for a given filament size, but the increased fineness of filament attainable by stretch spinning offsets this factor and tends to maintain the flexibility of the yarn.

Yield Point:

An autographic record of the stress-strain relationship of a rayon yarn will show for most yarns a definite yield point at about one-half the breaking load. At this point the yarn flows rapidly under little or no increase in load. Beyond it the load-elongation proportionality is resumed again but at a different slope than in the early part of the curve. The location of this yield point and the ultimate values of strength and perhaps elongation also are affected by the speed of testing because of the flow and after-effect phenomena described above. Thus the micellar structure is responsible for the need which the rayon specification has met, of specifying an exact procedure for the testing of strength in order that the results of various laboratories may check one another. The determination of elongation should be included in the next revision of this specification.

TABLE II.—MOISTURE ABSORPTION OF CELLULOSIC MATERIALS IN SATURATED AIR ACCORDING TO SHEPPARD AND NEWSOME.

TYPE OF CELLULOSE	PERCENTAGE REGAIN AT 30° C. AND 100 PER CENT RELATIVE HUMIDITY
Cotton linters	15.0
Hydrocellulose (acid treatment)	10.4
Standard cellulose (A.S.T.M. procedure)	17.5
Hydrated cellulose "A" (cotton mercerized without tension)	22.7
Hydrated cellulose "B" (regenerated from cuprammonium solution)	23.5 (cuprammonium rayon)
Hydrated cellulose "C" (regenerated from cellulose acetate)	26.6 (saponified acetate rayon)
Cellulose triacetate (completely acetylated)	8.3
Cellulose acetate film base (partially acetylated)	15.0 (acetate rayon)
Cellulose nitrate (10.8 per cent nitrogen content)	5.0
Cellobiose octacetate (completely acetylated)	1.0
Glucose pentacetate (completely acetylated)	0.8

The Nature of Moisture Absorbtion:

Cellulose is a very hygroscopic material, being sensitive to the moisture in the atmosphere, especially when in the form of fine fibers or filaments which have a large exposed surface per unit weight. At a given relative humidity the amount of moisture absorbed depends upon the form of the cellulose or cellulose derivative.

Table II gives the moisture absorbed (as a percentage of the dry weight) at 100 per cent relative humidity for a number of materials as determined by Sheppard and Newsome of the Kodak research laboratories. Two facts stand out: First, the amount of moisture absorbed decreases as the orientation of the micellae is increased. Second, the moisture absorbtion decreases as the hydroxyl groups are replaced chemically by acid radicals. Both of these observations indicate that the water molecules must be attracted and held by the residual forces of the hydroxyl groups along the exposed sides of the micellae. By better orientation or by chemical replacement the number of free OH groups which can attract water is reduced.

The fact that even the completely acetylated triacetate shows considerable absorption indicates that a second factor is also operative in this case, but not in the case of the completely acetylated cellobiose or glucose. This factor is apparently the capillary action of the pores in the micellar network. This capillary effect accounts for the well-known hysteresis observed in connection with the absorption and desorption curves of the moisture content - humidity relationship. Filaments which approach equilibrium with a given humidity from the wet side show a greater regain than when they approach equilibrium with the same humidity from the dry side. This is apparently due to a locking in of the water molecules which have entered the pores as the pore spaces at the surface contract during drying.

The Effects of Absorbed Moisture:

The tremendous influence of this moisture absorption or swelling phenomenon on the properties of rayon are explainable in the light of the micellar structure. The absorbed moisture pries the micellae farther apart and so reduces the mutual attractive forces. It acts at the same time as an internal lubricant enabling them to slide and shift on one another more easily. Consequently the strength of the wet filament is lower and the elongation higher than that of the dry. Because of the sensitivity of air-dry tests to changes in humidity a definite humidity for preparing and testing rayon is specified. Because of the difficulty of maintaining accurate humidity control, most rayon plants and many consumers control their quality by wet tests whose incorporation in the rayon specification is now under consideration. Within the limits of relative humidity occurring in practice, the moisture content, and hence the strength of rayon, increases almost linearly with increasing humidity. Changes in humidity affect the properties of acetate rayon only about half as much as those of the other types because its moisture absorption is about half that of the others.

The increased internal lubrication due to the presence of moisture greatly increases the plasticity. This affects not only the ease with which rayon flows or elongates under load, but also the rigidity of the filaments. For this reason a certain degree of humidity is very desirable in textile processing. The adverse effect upon strength and plasticity is more than offset by the improvement in limberness or pliability which facilitates the formation of perfect interlacing in weaving and perfect stitch formation in knitting. Although various softening oils are used in this connection, nothing takes the place of moisture in penetrating and softening the structure of cellulose.

Another paper could be written on the relation between micellar structure and the chemical and dyeing properties of the rayons. Suffice it to say that the regenerated rayons as a group, being more open in structure than the native cellulose fibers, are more sensitive to chemical action and to dyes. Yarn which is held during dyeing under sufficient tension to stretch it, comes out lighter than unstretched yarn dyed in the same bath. Apparently the improved orientation of the stretched yarn has reduced the attraction for dyestuff probably by closing some of the pores as well as by the reduction of the free hydroxyl groups.

If it were not for the swelling of the cellulose structure in water, dye penetration would be impossible. For example, dyes which will dye rayon from a water solution will not dye it from a solution in an organic solvent which has no swelling action.

The acetate rayons are impervious to most direct cotton and rayon colors. This is no doubt due in part to the reduced swelling in water and in part to the replacement of OH groups by acetyl groups. A complete range of special acetate dyestuffs has been developed however. Most of these dissolve in or diffuse through the cellulose acetate in accordance with the laws of true solutions. They form, in fact, solid solutions in the acetate filaments.

While this review of the present knowledge of the structure of the rayons by no means exhausts the subject, it does indicate how research on cellulose is providing that knowledge of the material rayon, which is of value to the Society in its work and to all others who are concerned with its behavior and its utilization.

DISCUSSION

Mr. W. F. Edwards.[1]—Mr. Smith has started out with a glucose molecule and he shows a lot of things about its relation to the cellulose molecule and refers to a recent announcement of the synthesis of cellulose from glucose by the action of enzymes. Much that we know about glucose and cellulose chemically has been developed in attempts to find out what is the matter with glucose in fermentation processes. It has been found that glucose sometimes fermented and gave about so much alcohol but at other times it did not work. It was known, as I said in my paper,[2] that enzymes had very markedly specific actions and that sometimes they did not seem to work, and that led to a great deal of research. The literature is full of the work to determine what makes one glucose do one thing and another glucose do another thing with apparently the same enzymes. The result was that we have at least six well-defined glucoses that we known chemically very well. We have also learned that enzymes have variable characteristics--they look alike and they act alike mostly but not altogether —and this has led to a great deal of work.

Mr. H. deW. Smith.[3]—Professor Hibbert of McGill University has published a paper on an enzyme which describes how he has produced cellulose membranes from glucose solutions. If this work is confirmed, it is the first synthesis of cellulose that has ever been accomplished and is a very important example of enzymatic action.

Mr. K. B. Cook.[4]—I should like to ask in testing rayon yarns at what percentage of the breaking load does the stretch of yarn attain a permanent set?

Mr. Smith.—It is commonly believed, I think, that the yield point, which occurs at approximately half of the breaking load, is the point beyond which we have a permanent elongation and that below that the material is truly elastic, but the time element enters there. You can load rayon to produce an elongation of as little as 2 per cent, and if it is under that load for any length of time it takes a permanent set by flowing, that is, a rearrangement of the internal structure, but if you elongate it rapidly to 2 per cent and release it you get an immediate recovery. If it is not held too long under the load it may come back part way when released and then creep back slowly to its original length. The true elastic limit of viscose rayon is not very far from 2 per cent—I mean having due regard for the time effect—but for rapid loading and unloading the yield point is fairly safe as a criterion of the point beyond which the yarn is permanently damaged.

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[1] Director of Laboratories, United States Testing Co., Inc., Hoboken, N. J.

[2] See p. 725.

[3] A. M. Tenney Associates, New York City.

[4] Technical Manager, Manville Jenckes Co., Manville, R. I.

MR. L. A. GRAYBILL.[1]—I should like to ask Mr. Smith if anybody has succeeded in spinning rayon filaments with a spiral orientation of the micellae such as he described for cotton.

MR. SMITH.—Not that I know of. It is difficult enough to get the micellae lined up without undertaking to make them form a spiral.

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[1] Chief Technologist, Bibb Manufacturing Co., Macon, Ga.

THE SUTER-WEBB COTTON FIBER DUPLEX SORTER AND THE RESULTING METHOD OF LENGTH-VARIABILITY MEASUREMENTS

BY ROBERT W. WEBB[1]

SYNOPSIS

All raw cotton consists of fibers of many different lengths intermingled in various proportions. The utilities and values of different cottons are affected by the length and variability of length of their fibers. In order, therefore, to deal with these factors of quality in problems of utilization, marketing, and breeding it is important to measure accurately the lengths and distribution of lengths of fibers in given samples of cotton.

Instruments and methods for this purpose devised by Johannsen, Baer, Balls and others are described in the literature. To attain greater accuracy, ease, and rapidity of operation an improved cotton fiber sorter, embodying certain new features, has been developed as described in the paper, together with the methods employed in its use. Some data are presented to show the limits within which the results can be duplicated.

All raw cotton consists of fibers of many different lengths intermingled in various proportions. The utilities and values of different cottons are affected by the length and variability of length of their fibers. In order, therefore, to deal with these factors of quality in problems of utilization, marketing, and breeding it is important to measure accurately the lengths and distribution of lengths of fibers in given samples of cotton. Instruments and methods for this purpose devised by Johanssen, Baer, Balls and others are described in the literature. To attain greater accuracy, ease, and rapidity of operation an improved cotton fiber sorter, embodying certain new features, has been developed with the cooperation of Mr. Alfred Suter. This paper will describe the machine and the methods employed in its use.

The apparatus, as will be noted in Fig. 1, consists of two independent and closely adjacent fields of lower combs arranged in the same horizontal plane and allowing similar working distances. Each lower comb is controlled by a simple releasing device, and may be dropped vertically during the process of sorting or may be entirely removed for cleaning after sorting. The vertical movement of the combs by its very action and by the opportunity which it affords

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[1] Senior Cotton Technologist, Bureau of Agricultural Economics, U. S. Department of Agriculture, Washington, D. C.

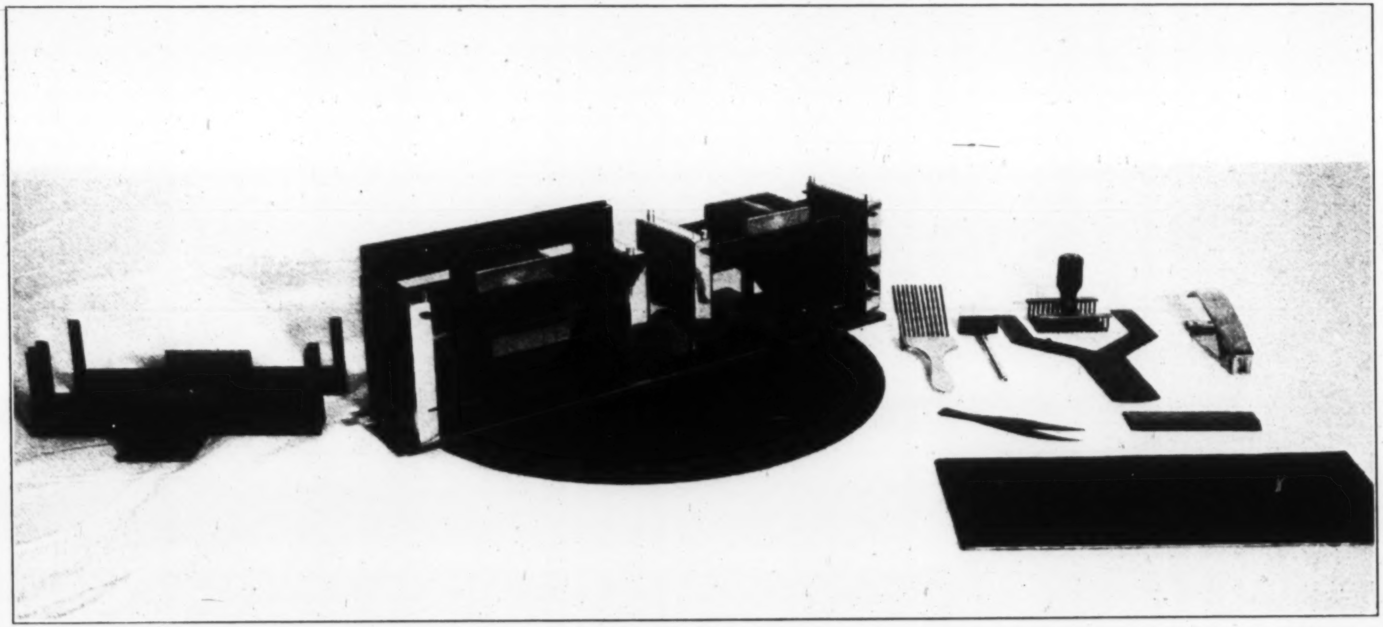

FIG. 1.—Suter-Webb Cotton Fiber Duplex Sorter and Accessories, Approximately $\frac{1}{10}$ Natural Size.

the operator to support the protruding tuft of fibers, if necessary, causes a minimum of disturbance to the arrangement of the fibers in the sample. A complete set of top combs is available which may be used in connection with either field of lower combs, and which permits a considerable variation in number, arrangement, or combination of combs during the entire or any part of the sorting process, as occasion demands. As a consequence, the fibers may be double-combed, if desired, with a minimum of friction throughout their entire length by means of only one upper comb properly situated. One of the most desirable features of the apparatus, perhaps, is that it may be revolved easily and quickly, thus permitting a reversal of the fiber bundle without its removal from or disturbance in the combs. This provision for revolution, moreover, allows a wide range of positions for the machine which facilitate ease of its operation at different stages by different operators. Air currents in most fiber laboratories suggest the desirability of sorting fibers under a hood, and the duplex sorting machine, being small and compact, is well adapted to such conditions.

Because of their structure, hygroscopicity, and tendency to disarrangement in mass, several necessary precautions and much care must be exercised in handling the fibers. Variations in humidity appreciably affect cotton fiber properties and characteristics making it necessary to condition, prepare, array, and weigh the fibers under controlled conditions of the atmosphere for most satisfactory operation and accurate results. A temperature of 70° F. (21° C.) and a relative humidity of 65 per cent have been found satisfactory.

In ordinary sorting, a composite sample of fibers aggregating 6 to 8 g. is obtained by taking with the hand a pinch of fibers weighing approximately $\frac{1}{2}$ g. from each of at least 12 different positions in the sample. These pinches are grasped in the hand and are thoroughly mixed by gently pulling and lapping. This lapping is repeated a number of times, depending upon the nature and the condition of the cotton, and care is exercised not to lose or break any of the fibers. Approximately 300 mg. of the fibers are withdrawn from the cross-section of this mix, the fibers thoroughly mixed by removing a few of the fibers at a time with the hand, as long as they last, and superimposing them upon each other. A 75-mg. portion is withdrawn for sorting. The only weighing made is with the 75-mg. bundle; the other weighings are merely mentioned in order to permit uniformity in the procedure of sampling.

The fibers are rolled gently by hand into a bundle and are further straightened and paralleled. No single step in the sorting operation influences the degree of success of sorting as does the initial prepara-

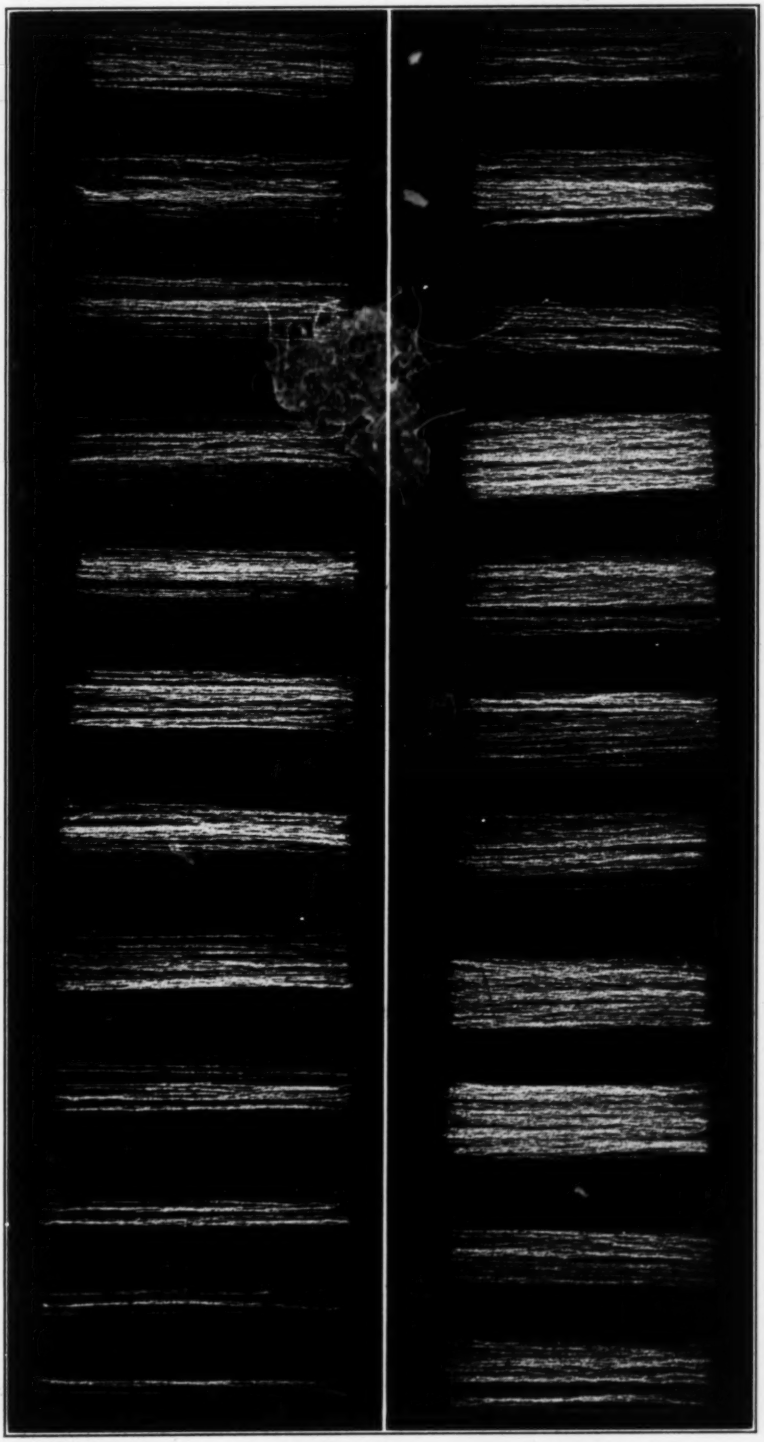

FIG. 2.—Showing the Fiber-Length Array, Natural Size, From a Cotton Classed $1\frac{5}{32}$ in. Staple Length. (Note that the fiber lengths range from $1\frac{3}{4}$ to below $\frac{1}{8}$ in., see also pp. 768 and 769.)

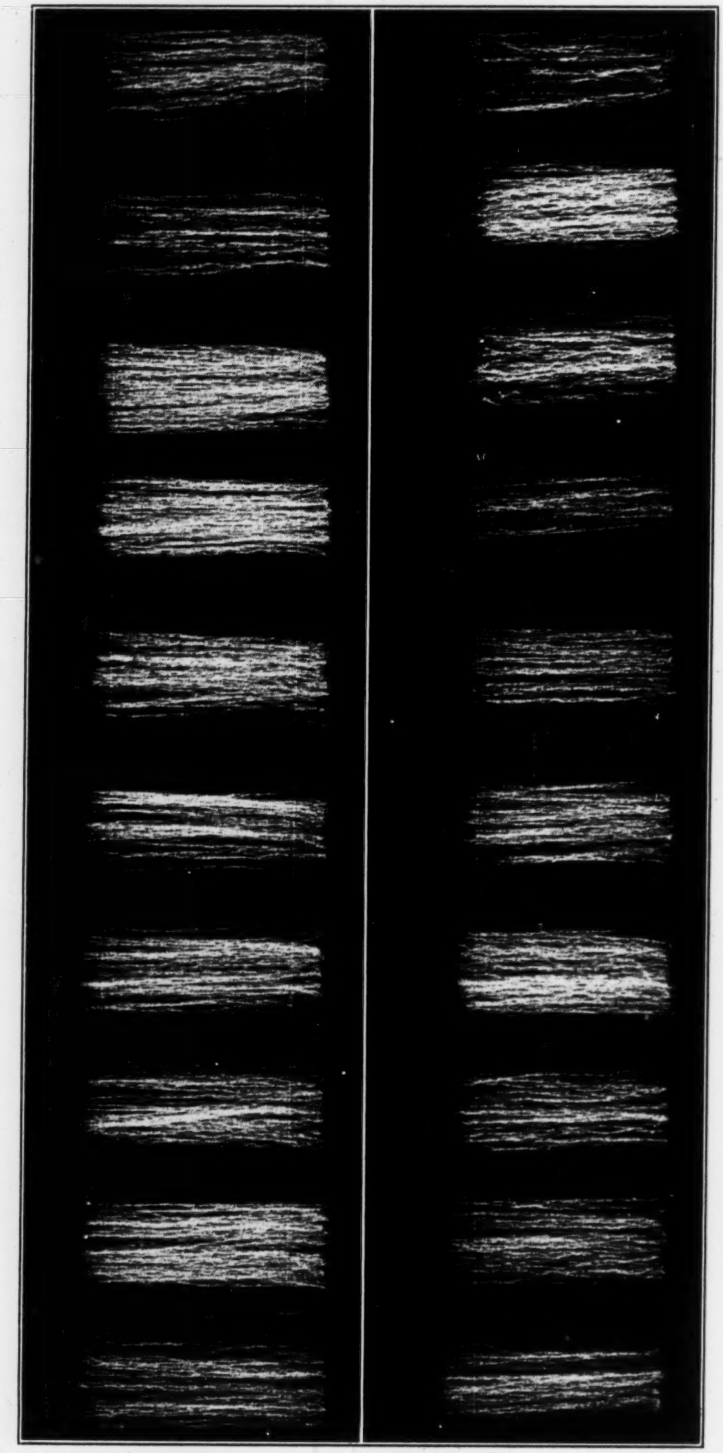

FIG. 2.—*Continued.*

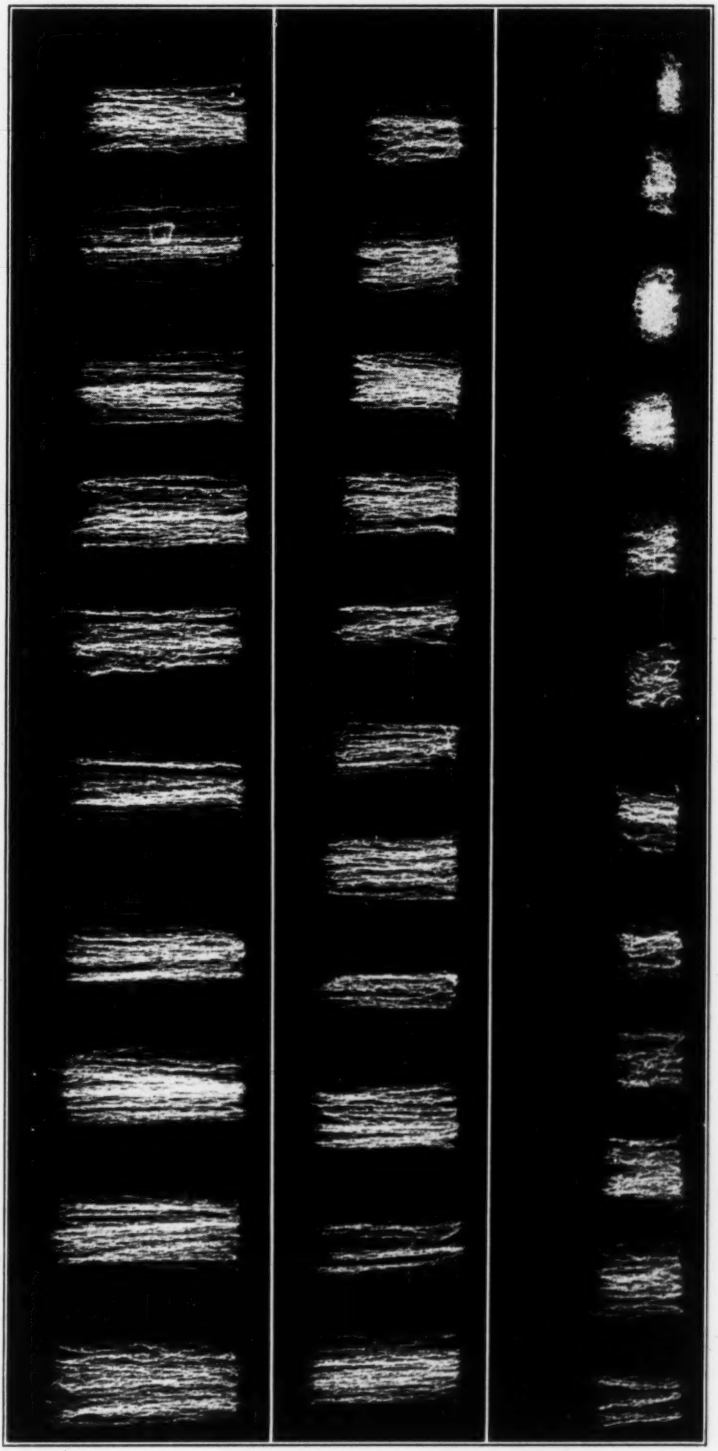

FIG. 2.—*Continued.*

tion of the fibers in the bundle. Mechanical laboratory devices for drawing small samples of cotton fibers into sliver or similar forms have been developed. However, before they can be generally adopted and recommended in this connection, either it must be adequately proved that they do not disturb the distribution of fiber lengths in cottons representing a wide range of qualities, or else the nature and extent of the changes must be accurately determined for different kinds and types of cotton.

The prepared bundle of fibers is now placed in the left field of lower combs and, if necessary, a sufficient number of top combs is inserted to prevent slippage. With fiber forceps of the usual type, a relatively small number of fibers are removed successively and placed perpendicular to a common base line in the right field of lower combs. In line with methods previously described by others, this operation is repeated until all of the fibers are transferred, the combs in the left field being dropped or removed, as occasion demands. Especial attention is given to the straightening and paralleling of the free portions of the fibers and to the arrangement of one end of the fibers perpendicular to a common base line.

Revolving the machine 180 deg., the right field of combs containing the bundle of fibers now becomes the left field and the ends of the bundle are reversed. Top combs are inserted, as needed, and the fibers are similarly transferred a second time, care being exercised not only to further straighten and parallel the fibers but to arrange one end of the fibers perpendicular to a common base line with a greater degree of accuracy than previously. After all of the fibers have been transferred, the alignment of the ends to a common base line may be further improved by carefully withdrawing those which protrude and properly returning them to the bundle.

The machine is again revolved 180 deg.; the bundle becomes reversed and takes its place on the left side; then top combs are inserted. Held in such a position, the fibers of different lengths may be readily sorted and arranged in the form of an array on a black velvet. The longest fibers are removed first, followed in order by the shorter lengths. Such an array not only represents all of the different lengths but also indicates the relative quantity of each length in the sample (Fig. 2).

The total number of fiber groups composing an array generally range from 75 to 150, depending upon the staple length of the sample, and aggregate approximately 73 to 74 mg. The large number of fiber groups, representing as many different cross-sections of the bundle, and the relatively small loss of fibers are conducive to refinement in sorting and accuracy of results. Finally the fiber groups are measured; combined in groups of $\frac{1}{16}$ in. intervals; wrapped in papers, properly identified; allowed to condition under controlled atmospheric conditions; and weighed on micro-chemical or micro-torsional balances.

From the data thus obtained, the percentages by weight of each length and of the cumulative lengths are readily calculated and may be plotted, if desired, as successive and cumulative frequency curves. Moreover, various statistical expressions such as coefficients of variability, skewness, and kurtosis can be calculated from such basic data for describing the fiber length frequencies in a sample and for comparing the frequencies in different samples.

Repeated tests have been made on samples from a particular lot of cotton by the same and different laboratory workers. The results obtained have shown an unusually high degree of consistency. For instance, a statistical study involving 45 1-in. cottons and 130 length arrays has shown that the results can be duplicated within limits, as follows:

NUMBER OF SORTINGS	PROBABLE ERROR OF THE MEAN, IN.
2	± 0.0105
3	± 0.0075
4	± 0.0053
5	± 0.0047
6	± 0.0043
7	± 0.0040

Analyses, moreover, have been made on synthetic samples in which the fibers were cut to represent one, two or more different lengths. The results obtained from sorting such samples have agreed well with the data which served as a basis of preparation. It is felt, therefore, that, even though the personal equation has not been entirely eliminated, it has been greatly reduced and that the results embody both accuracy and precision of a high order.

The amount of time required for a complete determination varies with the operator, the staple length, the refinement in sorting desired and the accuracy of results demanded. A total of approximately 1½ hours is generally required by a skilled operator to perform a test; that is, the actual work of preparing the bundle, sorting the fibers, and making the necessary measurements, weighings and calculations.

Information of this type is assisting in establishing a more intelligent and stable basis for: cotton breeding and production; ginning efficiency; standardization of staple length concepts, graduations and descriptions; and utilization of cotton fibers in manufacturing. The method of sorting fibers and the results of various studies now under way or proposed will appear in future Government publications.

DISCUSSION

Mr. W. D. Appel[1] (*presented in written form*).—The cost of manufacture and the properties of cotton yarn and cloth depend upon the dimensions and properties of the individual fibers. Sampling and sorting are the first steps in the study of fiber characteristics. Sorting is a laborious process at best and one in which the personal equation of the operator is an important factor. The Suter-Webb cotton fiber duplex sorter not only simplifies the technique of fiber sorting, but it materially reduces the chances of error.

Of the numerous applications suggested by Mr. Webb, I should like to emphasize the value of this sorter for studies of the changes in distribution in lengths of fibers taking place in carding, combing, drawing and spinning. The relation of variations in machine settings to the character of the fibers removed and remaining in the yarn as well as to the properties of the yarn should be worked out in detail. The results may lead to more uniform, more economical, and better yarns than are produced commercially at this time.

Mr. R. W. Webb.[2]—We have been carrying on to some extent for the last several years the line of work to which Mr. Appel referred. However, a great amount of work is necessary before we can feel sufficiently secure to make any statements. During the last three years, we have been reserving from our experimental spinning, samples representing each machine's finished product and waste; analyzing certain of these; and making certain settings in each machine on the basis of that information. So far as I am aware, this is about the nearest approach that has been or is being made to put experimental spinning on a scientific basis.

Mr. J. M. Weaver.[3]—I should like to ask Mr. Webb regarding the results obtained with various samples. Do you get a constant degree of variability with all kinds of cotton?

Mr. Webb.—Yes, we get a more or less similar type of variability. We have found a relatively large amount of variability in the fiber lengths for all of the samples of cotton we have tested. In certain cottons where the fibers are removed very carefully from the seed by hand, we generally get a higher degree of uniformity of fiber lengths than that observed in samples of commercial-ginned lint. In the shorter lengths of the samples we get a considerable range of proportions and gradations. The question comes up: What is staple length? I have purposely avoided that subject as it is a difficult one to answer at the present time. The information we are accumulating is for that purpose. That is, we are endeavoring to find out what is staple length; what is meant by range and uniformity of fiber lengths; what is normal and abnormal uniformity; for a normal uniformity, how should staple length graduations be handled; and for a given staple length how should different degrees of uniformity be treated.

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[1] Chief, Textile Section, U. S. Bureau of Standards, Washington, D. C.

[2] Senior Cotton Technologist, Bureau of Agricultural Economics, U. S. Department of Agriculture, Washington, D. C.

[3] Sales Engineer, General Asbestos and Rubber Division of Raybestos-Manhattan, Inc., North Charleston, S. C.

MR. B. H. FOSTER.[1]—It would be of interest to know just what effect humidity and temperature would have on the array. Would the fibers be longer in length or shorter with lower humidity than with high?

MR. WEBB.—We have made a number of tests on samples of cotton under different humidities for a given temperature and we have found some indications of a trend. For instance, taking two extremes, we have observed that in general an array made at 85 per cent relative humidity is about $\frac{1}{32}$ in. longer than that made of the same material at 25 or 30 per cent humidity. Within a certain range, say 40 to 70 per cent relative humidity, I doubt if there is any detectable difference that can be determined by this method. Within limits and for certain comparative purposes, it does not matter what temperature or what humidity is employed in sorting or weighing, so long as the conditions are more or less constant throughout the entire process or for the whole array of a sample. That is, some of the errors or effects cancel out and do not reflect themselves in the calculations for the different percentages of lengths. There are further complications, of course, when we attempt to correlate the cotton classers' staple length designations with such laboratory data. That is, from a classing standpoint, our observations indicate that it is important to know whether or not the sample is in equilibrium with the atmosphere and whether or not the cotton classer is in equilibrium.

MR. FOSTER.—Are there any marked differences in arrays between American and Egyptian cottons?

MR. WEBB.—I am unable to answer that definitely because we have made only a limited number of tests. In general, however, I believe that we have observed a variability in fiber length of a more or less similar nature. I do not believe that we have made sufficient tests on Egyptian cotton to warrant a more specific comparison.

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[1] Manager, Textile Section, United States Rubber Co., Passaic, N. J.

MR. FOSTER.—Can this machine be used for other than cotton fibers—take, for instance, wool?

MR. WEBB.—We have never attempted to sort wool fibers with this machine. Since the principles involved appear to me to be more or less identical for cotton and wool, I feel that the machine with modification easily could be adapted to handle wool and other fibers. Each textile commodity has its own peculiar characteristics and properties.

MR. WEAVER.—Has this machine been developed to the point where it is ready for commercial use?

MR. WEBB.—If one has staple length types and desires to check on them, their gradations, their constancy, and things of that order, I should say that the machine and method is all right for commercial use. As for stapling the American cotton crop by the machine or for eliminating cotton classers, I would say that such a task is impracticable, if not impossible, at the present time and probably for a long time to come.

COLORIMETER AND METHOD EMPLOYED IN THE COLOR TESTING OF COTTON

By Dorothy Nickerson[1]

Synopsis

Describes a colorimeter for use in measuring and grading agricultural products which can be adjusted to measure either a small or a large area. Discusses the method of measurement by the use of disk mixture of Munsell papers which permits the expression of results in terms which adequately approximate the psychological attributes: hue, brilliance and chroma.

In solving the problem of color measurement for raw cotton standardization, a colorimeter has been developed by the color laboratory of the Bureau of Agricultural Economics in cooperation with the Keuffel & Esser Co. It has proved useful in measuring the color of many other agricultural products besides cotton—hay, meats, fruits and vegetables, butter, milk and cream, potatoes, etc., and although it is principally used in the textile field in relation to raw cotton, it may be applied to many other problems in textiles.

In the laboratory of the New Jersey Laundry Owners, for example, the efficiency of laundry equipment in its relation to the appearance and color of the washed goods is being measured by means of this instrument. Preliminary studies on the relation between raw stock and gray cloth have been made in our own laboratories. Under the direction of the Textile Section of the U. S. Bureau of Standards, an associate of the Cordage Institute is studying the color of cordage ropes.

The instrument is different in method from that of other colorimeters. First, and very important, its results may be expressed in *color* terms, that is, in terms that express the color as it is seen—in terms which adequately approximate the psychological color attributes: hue, brilliance, and chroma. Second, the instrument may be adjusted at will to measure either a large or a small area. Third, it measures the average color of a highly variegated sample as easily as it measures a uniform color. Fourth, it has a unique method of illumination by cross lighting. And fifth, the instrument is quick and easy to operate and calibrate.

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[1] Color Technologist, Bureau of Agricultural Economics, U. S. Department of Agriculture, Washington, D. C.

The method is simple in principle. The color of a sample is measured by varying the proportion of several color disks until the average color of the disks matches the color of the sample. The percentage areas of the disks exposed when the match is made are used to convert the color areas into terms approximating hue, brilliance, and chroma (defined in the Colorimetry Report of the Optical Society of America as *hue, brilliance,* and *saturation*). This is readily done by the use of disk mixture of Munsell papers.

The instrument is so constructed that the disk mixture is obtained by a moving optical wedge which collects the light from the exposed areas of the disks, thus allowing the disks themselves to remain stationary except as moved by the operator in order to adjust the relative areas exposed by the disks.

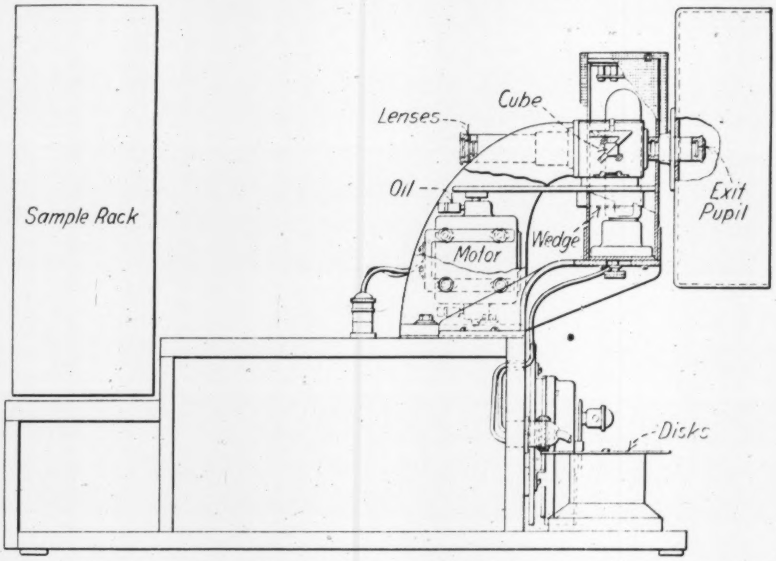

FIG. 1.—Showing Relative Positions of Disk and Samples with a Diagrammatic Side View of the Colorimeter.

Figure 1 indicates the relative positions of disks and samples, with a diagrammatic side view of the colorimeter. For textiles it seems generally useful to expose an area 4 in. in diameter for measurement. The area, however, may be increased to 12 in. in diameter by the use of an added lens, or reduced to a 1-in. diameter by the removal of these lenses.

The light from the sample is brought through a series of lenses, through the photometric cube, to be focused on the exit pupil. The light from the standard comparison disks is mixed by a revolving wedge and directed to the photometric cube, where its direction is changed, to be focused also upon the exit pupil. The sample field is uniform in color since the image seen is that of the cube, not of the sample itself.

The illumination is supplied by two lamps which are so placed that they are in a horizontal plane with the center of the sample and in a vertical plane with the center of the disks. Movie projection lamps, 50 volt prefocus base, having four coiled filaments in the same plane, are used in the instrument. The light given off at right angles to the plane of the four filaments is greater than that in the same direction when the lamp is rotated through 90 deg. By adjusting the lamps, the bases of which are provided with a slot and screw for this purpose, the light on the sample surface may be made equal to that on the disk surface. Such a method of light adjustment provides for darkening such samples as are too light to be measured with available disks, and lightening such samples as may be too dark to measure.

Tables have been prepared for use with several sets of disks in order to eliminate the calculation of hue, brilliance, and chroma from the disk areas. These tables do not cover the entire range of the spectrum colors as would be necessary in indiscriminate matching of textile samples, but it is hoped that such a series will be completed within a short time.

The precision with which observations may be made has been calculated for several observers. These figures have been published, together with observations regarding tolerances, training of observers, and color blindness in reports published by the Bureau of Agricultural Economics and may be obtained upon application.

FULL-LOAD CALIBRATION OF A 600,000-LB. TESTING MACHINE

By H. F. Moore,[1] J. C. Othus[2] and G. N. Krouse[3]

Synopsis

The paper describes the calibration of a screw-power, balance-beam testing machine of 600,000-lb. capacity. The calibration was made by the use of two 10,000-lb standard weights and an elastic bar fitted with a delicate strainometer. The elastic bar was used merely as a transfer instrument, and it was not necessary to evaluate its elastic constants. All that was necessary was to have a strainometer sufficiently sensitive that load on the bar could be reproduced a few moments later with a high degree of accuracy.

After 27 years of rather severe service the testing machine was found to still have a high degree of accuracy and sensitivity.

In the Materials Testing Laboratory of the University of Illinois there is a 600,000-lb., two-screw Riehle testing machine, fitted with guide columns, and hydraulic recoil buffers, and weighing the applied force by compound levers and a balance beam. The machine (Fig. 1) will take tension specimens 20 ft. long. This machine is 27 years old and was moved to its present location 2 years ago. It was decided to calibrate the weighing scale of this machine for accuracy and sensitivity after its 27 years of rather hard service, with the idea that the calibrated machine could serve as a general reference machine for the laboratory.

The method used was a combination of calibration by dead weights and the elastic bar. There were available two 10,000-lb. standard weights loaned by the U. S. Bureau of Standards. These weights were reported as correct within $\frac{1}{10}$ lb. The elastic bar was an alloy steel bar 19 ft. long and 4 in. in diameter. On this bar was placed a strainometer with a gage length of 100 in. On the micrometer dial gage of the strainometer one complete division represented approximately 0.00005 in. stretch of the bar.

The method of calibrating the machine is shown diagrammatically in Fig. 2. After balancing the machine at zero, the 10,000-lb. weights were let down upon the weighing table by means of the jacks and the framework shown in Fig. 2. The weighing beam of the machine was then balanced and the error at 20,000 lb. load directly determined. With the poise of the beam remaining in position to weigh this load, the weights were lifted by means of the jacks, and tension put on the elastic bar until the beam was again in balance. The reading of the strainometer was then noted. Then the weights were again lowered upon the table. This lowering of the weights slightly relieved the load on the elastic bar, causing the reading of the strainometer to "back off" a few divisions. The load was then applied by the screws until the reading of the strainometer was brought to that indicating 20,000-lb. pull on the bar. The sensitivity of the strainometer was such, that a change of pull as small as 50 lb. corresponded to a movement of one-third of a scale division on the strainometer dial. There was then on the weighing table 20,000 lb. of dead load and a 20,000-lb.

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[1] Research Professor of Engineering Materials, University of Illinois, Urbana, Ill.

[2] Assistant Professor of Mechanics and Materials, Oregon State College, Corvallis, Ore.

[3] Graduate Student in Mechanics, University of Illinois, Urbana, Ill.

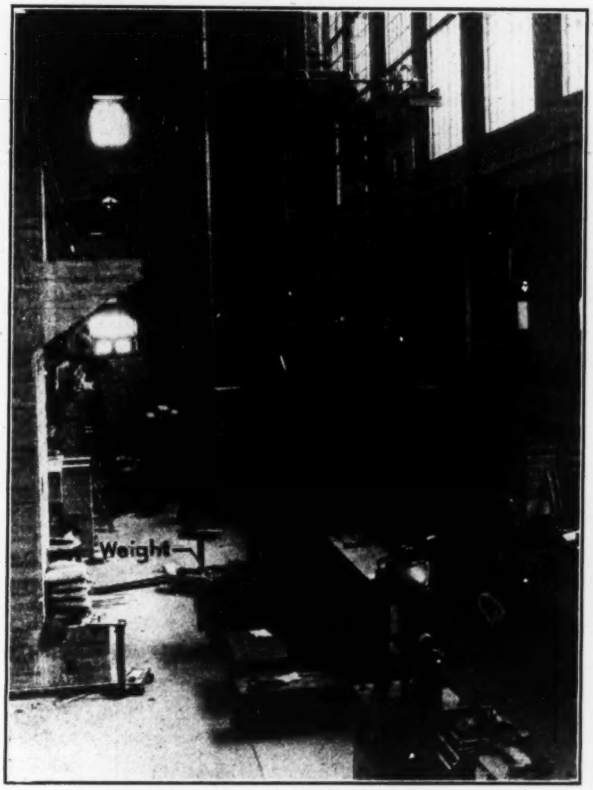

FIG. 1.—600,000-lb. Screw-Power, Balance-Beam Testing Machine.

The 10,000-lb. weights used for calibration can be seen resting on the weighing table at the floor level.

pull from the elastic bar—40,000 lb. in all. The beam was then balanced and read, and the error for the 40,000-lb. load determined. In like manner load was applied in increments of 20,000 lb. until the capacity of 600,000 lb. was reached.

The weighing beam of this machine is fitted with a magnifying pointer, or "needle beam," which markedly increases its sensitivity.

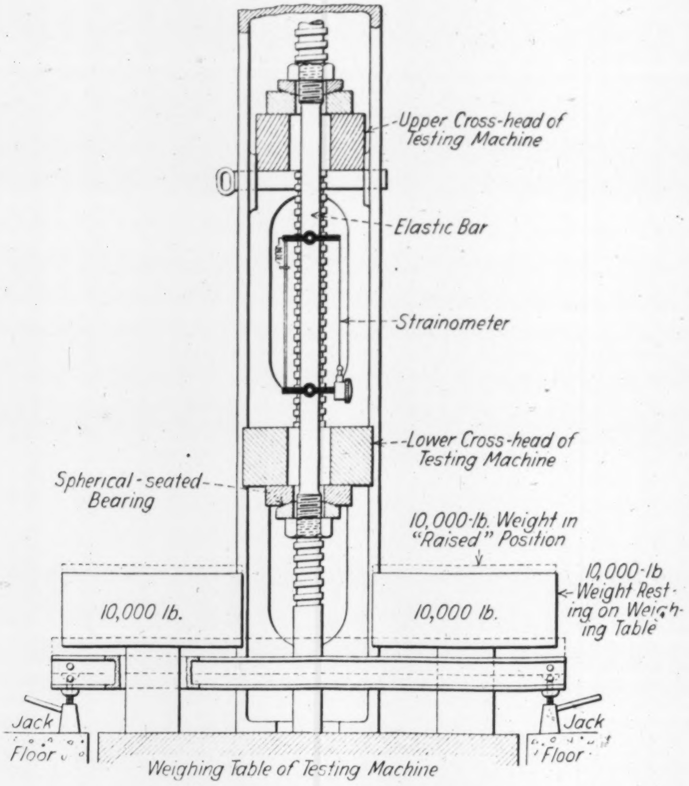
Upper Cross-head of Testing Machine
Elastic Bar
Strainometer
Lower Cross-head of Testing Machine
Spherical-seated Bearing
10,000-lb. Weight in "Raised" Position
10,000-lb Weight Resting on Weighing Table
10,000 lb.
10,000 lb.
Jack
Jack
Floor
Floor
Weighing Table of Testing Machine

FIG. 2.—Diagram of Calibration Rig.

It is possible to detect the variation of a 30-lb. load on the beam under any load. During the calibration tests the hydraulic recoil buffers were in place and were under a constant head of oil pressure. The tests were all run at night so as to secure as even temperature as possible, the only error due to temperature was that caused by temperature change between the time of putting a known load on the tension bar and the bringing of the strainometer reading to the same indication after the standard weights had been applied to the machine. The temperature at the middle of the length of the bar never varied a perceptible amount during such an interval. It will be noted that it is not necessary to evaluate the elastic constants of the bar. Sufficient sensitivity to reproduce a loading accurately is all that is required. Of course, any error in one reading is carried forward through successive readings, but there would be a certain amount of counterbalancing of such errors as the calibration proceeded.

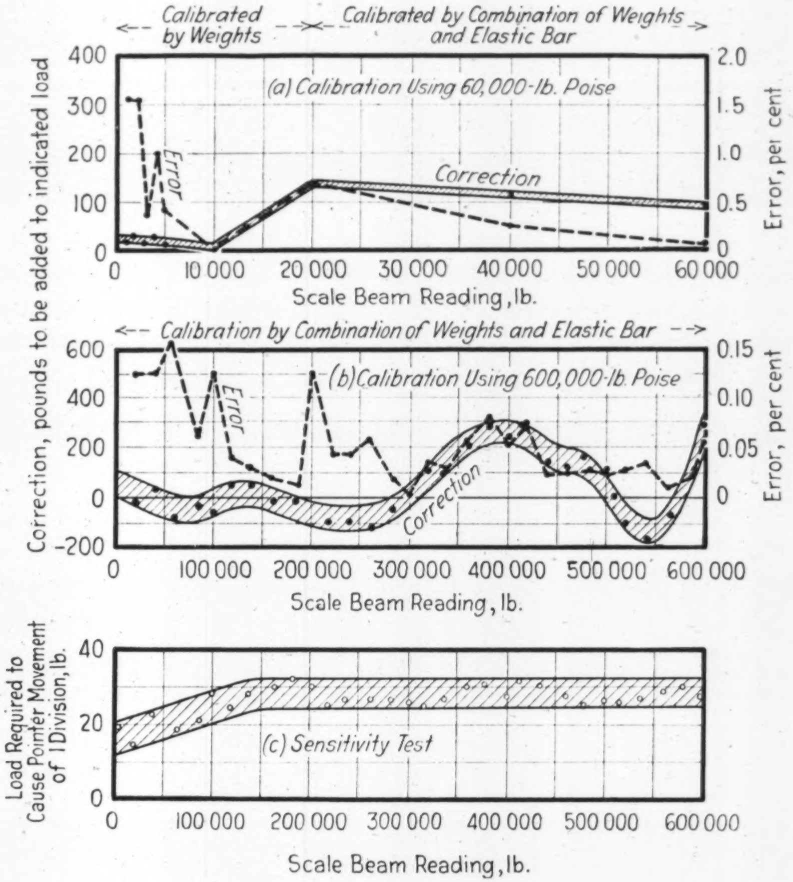

FIG. 3.—Results of Calibration.

In addition to the regular poise for weighing up to 600,000 lb. the testing machine is equipped with a light poise for weighing up to 60,000 lb. The machine was calibrated using this poise also. Up to 20,000 lb. the machine was calibrated directly with the standard weights, and with smaller weights which had been standardized by a comparison with a class B Bureau of Standards 50-lb. weight. Above

20,000 lb. the calibration with the light poise was made in the same manner as for the full-load poise.

Figure 3 shows graphically the results of the calibration. In place of drawing a line through the points denoting corrections, a band has been drawn with a width equal to the smallest division which can be read directly on the weighing beam of the testing machine —100 lb. for full-load poise and 10 lb. for the light poise. The loading ranges for the two poises with various tolerances are given in Table I.

TABLE I.—LOADING RANGE OF 600,000-LB. TESTING MACHINE AS DETERMINED BY CALIBRATION.

TOLERANCE, PER CENT OF INDICATED LOAD	LOADING RANGE, LB.
	USING LIGHT POISE (CAPACITY 60,000 LB.)
1.0	4000 to 60 000
0.5	30 000 to 60 000
0.2	45 000 to 60 000
	USING HEAVY POISE (CAPACITY 600,000 LB.)
1.0	20 000[a] to 600 000
0.5	20 000 to 600 000
0.2	20 000 to 600 000
0.1	222 000 to 600 000

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[a] Lowest test load using heavy poise was 20,000 lb.

The sensitivity of the machine at various loads was determined by adding dead weights to the table of the machine; and the index of sensitivity was taken as the weight necessary to move the magnifying pointer attached to the weighing beam over one division of its scale. This, as may be seen from Fig. 3 (*c*), amounts to about 30 lb. maximum.

Although the machine has been in severe service for 27 years, both its accuracy and sensitivity seem to be highly satisfactory.

AN AUTOMATIC AUTOGRAPHIC EXTENSOMETER FOR USE IN TENSION TESTS OF MATERIALS

By R. L. Templin[1]

Synopsis

The purpose of this paper is to describe an automatic autographic extensometer which has been developed in response to a demand for an inexpensive, accurate method for determining yield strengths of materials in routine tension tests. The instrument provides a means of obtaining load-strain curves at strain magnifications varying from about 400 to about 16,000. For commercial routine tests magnifications of 400 or 800 are used, and yield strengths can be obtained with an accuracy comparable to the usual values for ultimate tensile strength. A complete description of the extensometer is presented and typical load-strain curves are reproduced. While the instrument has been designed primarily for tension tests, it can also be used for compression tests without modification

The proposed new methods for determining the tensile yield strength of metals[2] can be used to much better advantage when more accurate, faster and lower-cost extension measuring apparatus is available. This is especially true for metals which do not have "yield points" as we think of the property in the case of hot-rolled mild steel. Evidence of the need for better apparatus may be readily inferred from the proposed provisions contained in the last paragraph of Appendix III of the 1931 Report of Committee E-1 on Methods of Testing wherein certain short-cut approximate methods are recommended which may be used upon agreement between producer and consumer.

Recognizing these facts, in the Aluminum Research Laboratories we have attempted to develop an automatic autographic extensometer for use in tension tests of materials. The requirements of satisfactory apparatus of this type are indeed both severe and numerous. Experience indicates that such an instrument should have a magnification ratio of at least 250 and preferably 500 to 1000. Its accuracy and sensitivity should be equal to those of the better commercial extensometers now available. It should be able to repeat within close limits and if possible should record deformation with decrease, as well as with increase, in load. It is quite desirable to be able to attach the instrument to various sizes of test specimens ranging from small diameter wires and thin sheet metal specimens up to the larger tension test specimens now in general commercial use. In the case of the smaller specimens it is evident that the part of the instrument attached to the specimen should be as light as possible. The instrument should be so designed as to permit of its functioning properly at speeds of testing corresponding to those now in use in routine commercial laboratories. Since the apparatus is to be used in routine commercial tests, it must be easy of manipulation and as rugged as possible in its design so as to withstand a reasonable amount of abuse. Unless the apparatus can be readily adaptable to existing testing machines its use would, of course, be considerably limited. As in other testing apparatus, the personal equation of the operator should be reduced to a minimum. Finally the cost of the instrument must be reasonable.

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[2] Proposed Definitions of Terms Relating to Methods of Testing, Appendix III, Report of Committee E-1, *Proceedings*, Am. Soc. Testing Mats., Vol. 31, Part I, p. 602 (1931).

With these requirements in mind a number of designs of such an instrument have been tried out with rather encouraging results.

DESCRIPTION OF APPARATUS

Most commercial testing machines are or can be readily provided with a recording drum and a pencil or stylus which while in contact with the drum is caused to move parallel to the axis of the drum, distances directly proportional to the amount of load applied to the specimen. Taking advantage of these facts it then becomes only necessary to provide ways and means for causing the drum to rotate by some amount which is directly proportional to the deformation occurring over a specified length of the test specimen during the application of load. The power required to rotate the drum and operate the connecting apparatus between the drum and the test specimen is large in comparison with the forces available in the apparatus which can be attached to the test specimen. It is necessary, therefore, to provide an additional source of power which must be controlled by the deformation occurring in the test specimen.

Since tension test specimens having a gage length of 2 in. are quite widely used, it was decided first to design an instrument suitable for such specimens. The use of a 2-in. gage length gives the first multiplication factor of two for the unit deformation. As a result of experience with other types of strain-measuring devices, it has been found that a single mechanical lever multiplication ratio of 5 to 1 is in general more satisfactory than larger ratios. Accordingly in the present instrument a bell-crank lever of that ratio has been provided, making the total ratio thus far 10 to 1. At this point in the amplifying system it is convenient to change from a nominal linear motion to one of rotation which, of course, is the motion of the final recording drum. This is accomplished by means of a suitable fine-thread lead screw, usually 50 threads per inch, which is so arranged that it becomes part of an electrical circuit and upon making or breaking contact with the lever, controls the force operating the recording apparatus. One end of the screw is provided with a simple universal joint which can be easily connected or disconnected.

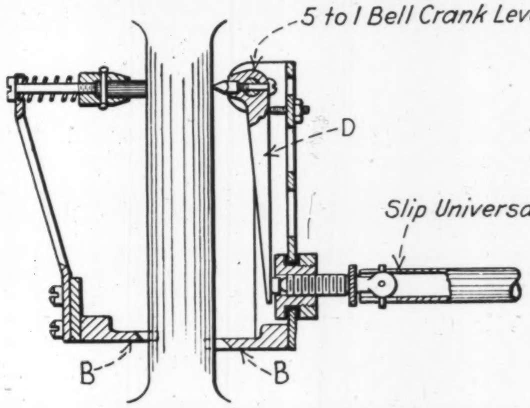
5 to 1 Bell Crank Lever
D
Slip Universal Joint
B
B

FIG. 1.—Section Through Strain Follower Showing Bell Crank and Contact Screw.

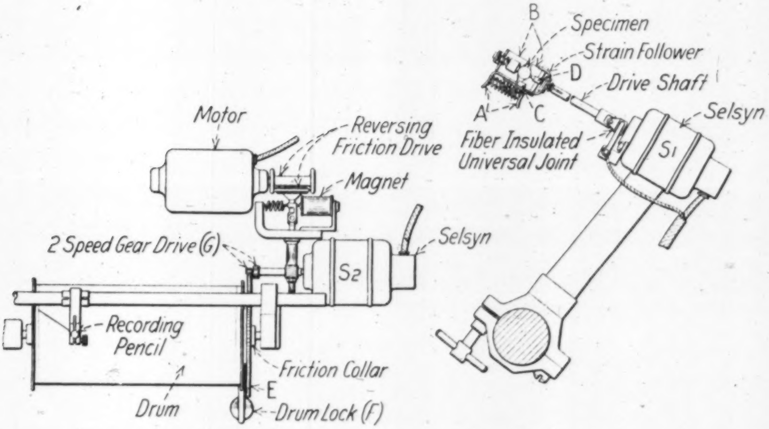
B
Specimen
Strain Follower
D
Drive Shaft
Selsyn
A
C
Motor
Reversing Friction Drive
Fiber Insulated Universal Joint
S1
Magnet
Selsyn
2 Speed Gear Drive (G)
S2
Recording Pencil
Friction Collar
E
Drum
Drum Lock (F)

FIG. 2.—Schematic Sketch of Automatic Autographic Load-Strain Recorder.

Experience has shown that when carefully prepared, straight specimens are tested in tension, using self-aligning grips, measurement of strain on only one element or side of the specimen is sufficient for determining yield strength. Taking advantage of this fact and using the details just described, a strain-following device shown in Figs. 1, 2 and 4 was developed. This element of the strain-recording apparatus weighs but 2 oz. and can be readily attached to the specimen by merely squeezing the two projections *A* between the thumb and finger, then releasing so as to grip the specimen between the self-centering knife edges *B*. For specimens $\frac{1}{2}$ in. in width or diameter, the stop *C* affords a means of centering the upper part of the device. While the point of the bell-crank lever *D* can be used for flat and the larger round specimens, yet this point can be readily replaced with a knife edge for small diameter round specimens.

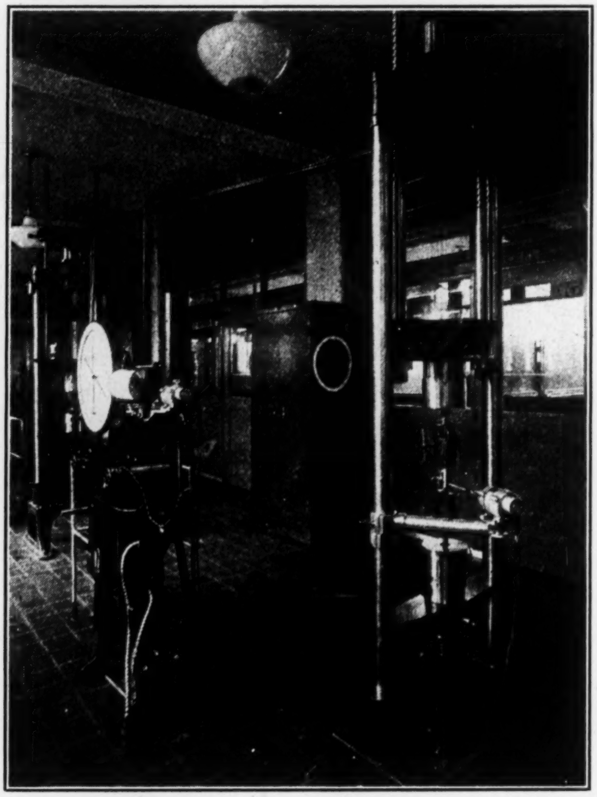

FIG. 3.—Photograph of Automatic Autographic Load-Strain Recorder.

The part of the apparatus which attaches to the specimen can be used on round specimens ranging from about 0.05 to 0.50 in. in diameter and on flat specimens $\frac{1}{2}$ in. wide ranging from about 0.01

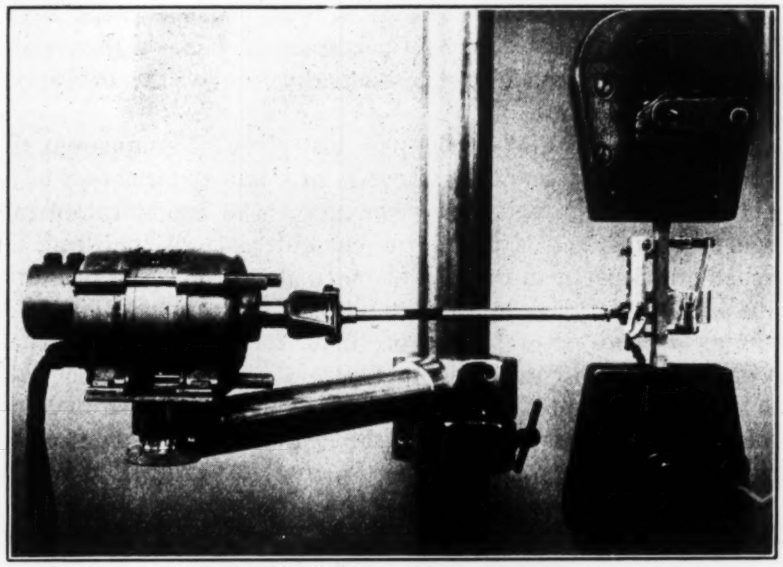

FIG. 4.—Photograph of Strain Follower.

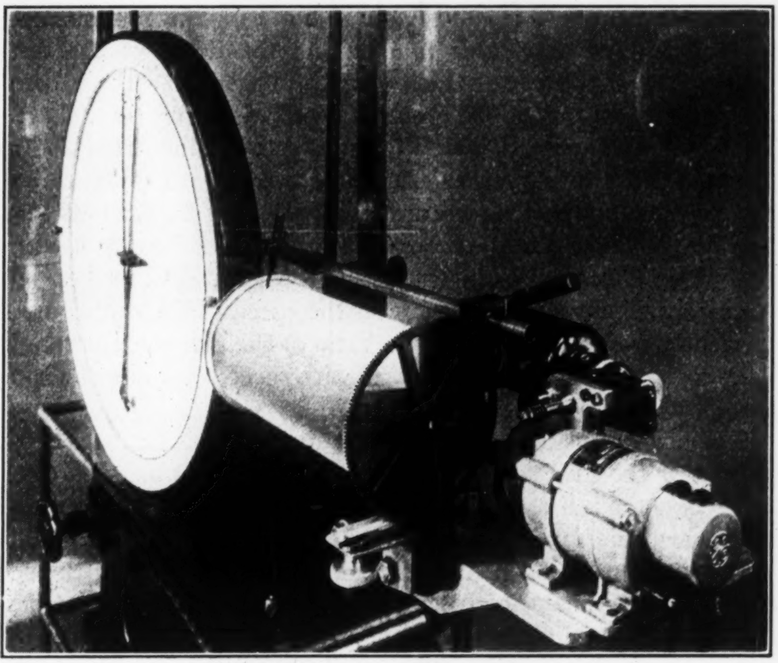

FIG. 5.—Photograph of Recorder Drum Mechanism.

to 0.50 in. in thickness. For large tension test specimens having reduced sections $1\frac{1}{2}$ by 8 in. by thicknesses of $\frac{1}{4}$ in. or greater it is necessary to use a modified but similar design of the device just described.

From the description of the part just given, it is apparent that one turn of the lead screw corresponds to a unit deformation in the specimen of 0.002 in. per inch. For an over-all magnification ratio of 500 to 1, it is necessary for the circumference of the drum and attached graph paper to rotate a distance of 1 in. for each revolution of the lead screw (or 2 in. for a multiplication ratio of 1000 to 1). Assuming a total circumference of 10 in. for the drum and chart, this distance would correspond to $\frac{1}{5}$ revolution for the higher ratio. This is readily provided for by using three gears as shown in Fig. 2. The largest gear, *E*, is attached to the end of the drum shaft or hub with a suitable spring-loaded collar so that the drum is driven by friction with the gear hub when not restrained by the brake lock, *F*. One or the other of the smaller gears, *G*, is meshed with the largest, *E*, according to the multiplication ratio desired. The rotation of the smaller gears is accurately synchronized with the rotation of the lead screw by the use of two Selsyn motors, S_1 and S_2, as shown in Fig. 2 and the photograph, Fig. 3. Each of these motors is mounted by means of suitable adjustable brackets on the frame of the testing machine, one near the specimen and the other near the recording drum. The shaft of the one near the drum, S_2, serves as a shaft for the smaller gears meshed with the larger gear on the drum and as a convenient place to locate the gear to be used for applying the additional power required to operate the apparatus. So far best results have been obtained using a worm gear and pinion having a ratio of about 80 to 1, or more, in supplying the additional power. The exact ratio will, of course, depend on the speed of the motor used to furnish the power, as well as on the ratio of the reversing mechanism. A variable speed motor has been used with success but one of constant speed simplifies the electrical circuit.

The driven member of the friction drive unit is made to contact with one of the driving disks on the motor shaft when the electromagnet is energized and with the other disk by means of a tension spring when the circuit is broken. The control of the electrical circuit is accomplished with the part of the mechanism on the specimen together with a sensitive relay or suitable grid-glow and amplifying tubes. The motor and electromagnet can be arranged to operate on either direct or alternating current, but the Selsyns must operate on alternating current, usually 60 cycle, 110 volts, single phase.

In making a test, the procedure is as follows: Insert the specimen in the machine, attach the control unit as previously described; swing the Selsyn unit S_1 near the specimen and adjust it for proper height so as to be opposite the lead screw of the control unit; connect the motor shaft extension to the lead screw making sure the screw is backed out far enough not to make contact with the bell-crank lever; witch on both Selsyns and the auxiliary motor; when the Selsyns

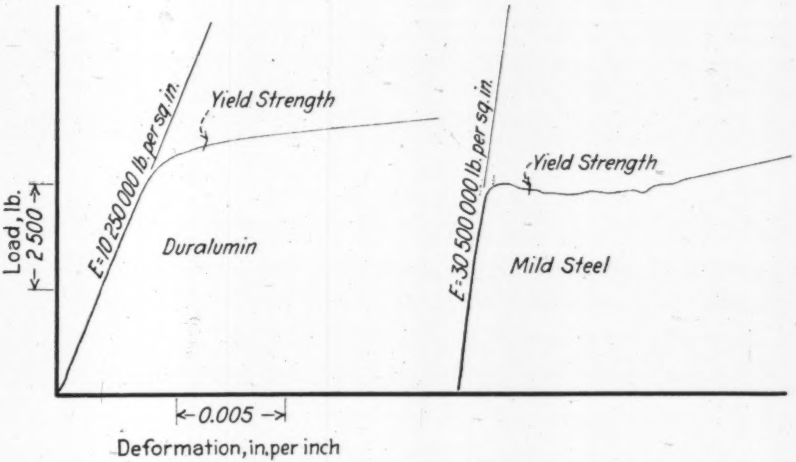

FIG. 6.—Load-Strain Curves for Duralumin and Mild Steel.

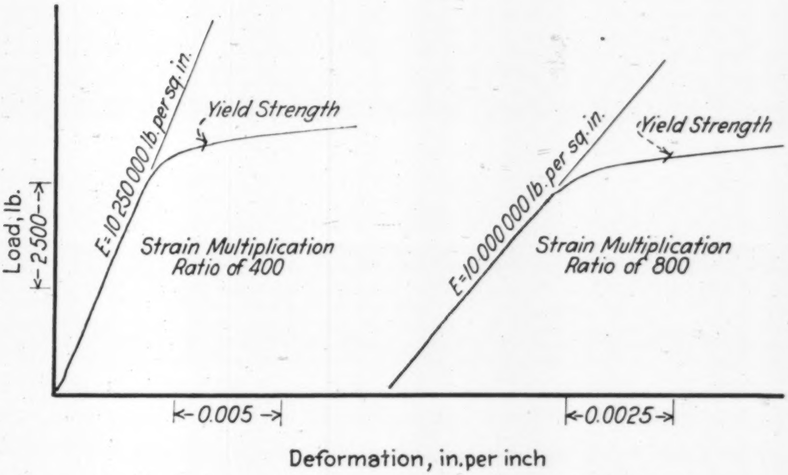

FIG. 7.—Load-Strain Curves for Duralumin with Strain Multiplication Ratios of 400 and 800.

cease running positively (when lead screw makes contact) release the recording drum and start loading the specimen. After passing the yield strength load appreciably, the Selsyns and auxiliary motor are switched off, the Selsyn S_1 near the specimen is swung out of the way and the control unit removed, without stopping the testing machine.

While these operations may appear numerous and somewhat complex, yet experience has shown that they actually require but a few seconds of time. The height of the Selsyn near the specimen requires but occasional adjustment, its shaft extension is quickly and easily attached to the control unit and a single switch starts and stops the Selsyns and the auxiliary motor. Changing from one magnification to another is but the work of a few minutes and with some refinements may be made by merely shifting a small lever.

Table I.—Calibration Data for Nominal 400-to-1 Magnification Arrangement of Autographic Extensometer.

Calibrating Device		Recording Drum		Total Magnification	Magnification
Total Movement, in.	Increment, in.	Total Movement, in.	Increment, in.		Per Inch for 2-in. Gage Length
0	0	0	0	0	0
0.0010	0.0010	0.382	0.195	195	390
0.0020	0.0010	0.581	0.199	199	398
0.0030	0.0010	0.774	0.193	193	386
0.0040	0.0010	0.969	0.195	195	390
0.0050	0.0010	1.167	0.198	198	396
0.0060	0.0010	1.366	0.199	199	398
0.0070	0.0010	1.563	0.197	197	394
0.0080	0.0010	1.760	0.197	197	394
0.0090	0.0010	1.957	0.197	197	394
0.0100	0.0010	2.161	0.204	204	408
0.0110	0.0010	2.355	0.194	194	388
0.0120	0.0010	2.553	0.198	198	396
0.0130	0.0010	2.748	0.195	195	390
0.0140	0.0010	2.948	0.200	200	400
0.0150	0.0010	3.149	0.201	201	402
				Average Magnification = 394	

It should be apparent that most of the parts of the instrument such as motors, gears and electromagnet, relay and tubes are commercial ones which can be readily obtained at a nominal cost. The control unit is simple, light in weight and rugged in construction, with the result that it is not expensive to make. The design of the apparatus permits of easy application to the majority of the various sizes and makes of present commercial testing machines.

Calibration of the apparatus using the device previously described before this Society[1] gave the results shown in Table I. Some sample load-deformation curves for steel and aluminum alloys are shown in Figs. 6, 7, 8 and 9, using nominal multiplication ratios of 400 to 1 and 800 to 1. On these curves the factor used as a criterion for determining yield strength was 0.2 per cent. The moduli of elasticity as determined from the curves are also indicated. Figure 8 shows the effects of release and reapplication of load after passing the yield strength and Fig. 9 the release of load in the normally considered elastic range of the material. In Fig. 9 the multiplication ratio for the two upper curves was 8000 and for the bottom curve 16,000. This extremely high ratio is obtained by using the regular 800 to 1 ratio, then interposing an auxiliary worm gear ratio of 20 to 1 between the control unit and the Selsyn motor S_2 as shown in Fig. 10. When using such high magnifications, best results are obtained when using low speeds of testing. With the normal magnifications of 400 to 1 or 800 to 1, satisfactory results are obtained using speeds of testing up to about 0.3 in. per inch per minute which cover the ranges of good com-

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[1] R. L. Templin, "The Calibration of Extensometers," *Proceedings*, Am. Soc. Testing Mats., Vol. 28, Part II, p. 714 (1928).

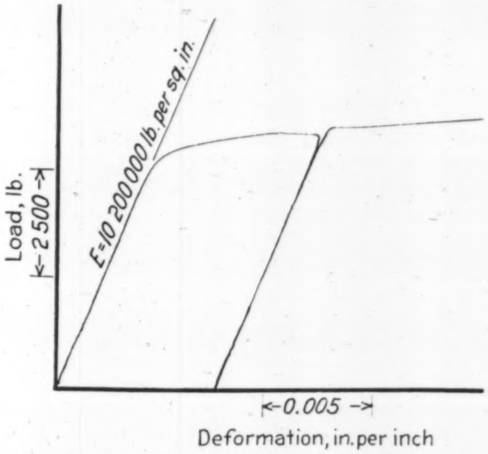

FIG. 8.—Load-Strain Curve Showing the Effects of Release and Reapplication of Load After Passing the Yield Strength.

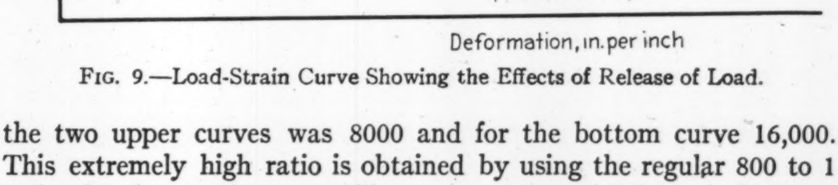

FIG. 9.—Load-Strain Curve Showing the Effects of Release of Load.

mercial practice. Still faster speeds can be used with somewhat different speed ratios in the auxiliary motor drive.

In conclusion, an attempt has been made to show that practical ways and means are available for making commercial routine yield strength determinations in tension tests of metals; that the values so determined may be expected to have an accuracy quite comparable to the usual values for ultimate tensile strength; and finally that the cost of such determinations need be but nominal. The apparatus also can with minor modifications be easily adapted to tests of a much higher order of precision.

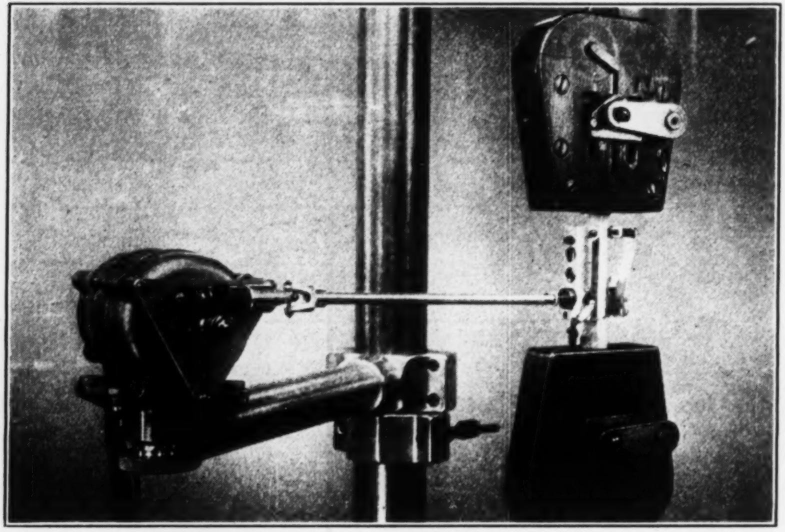

FIG. 10.—Photograph of Auxiliary Worm Gear.

While this instrument was designed primarily for tension tests, it will, of course, perform satisfactorily in compression tests.

Acknowledgment.—The author wishes to acknowledge the valuable assistance given by Mr. D. I. Bohn, Electrical Engineer, and Mr. C. Dumont, Testing Engineer, in the development of the apparatus just described.

THE ELECTRIC STRAIN METER AND ITS USE IN MEASURING INTERNAL STRAINS

BY R. E. DAVIS[1] AND R. W. CARLSON[2]

SYNOPSIS

This paper describes a remote-reading instrument, called the electric strain meter, which has been developed primarily to determine deformations and temperatures within mass concrete. Its operation for determination of deformation depends upon the known fact that within the elastic limit the electrical resistance of steel wire varies in direct proportion to stress in the wire. For the determination of temperature, the well-known relation between resistance and temperature of steel wire is employed. The design is such that temperature observations are not affected by deformation and that strain observations are not affected by temperature changes.

Representative test results from strain meters embedded in concrete are shown, indicating a close and consistent agreement between strain-meter readings and corresponding readings taken with a mechanical strain gage. Calibration has been found to remain constant over considerable periods of time.

INTRODUCTION

For the measurement of internal strains in concrete structures, it is necessary to use a measuring device which is embedded permanently in the mass. Obviously the calibration of such a device must remain constant in spite of the disturbing effects of time and moisture. In order to provide an instrument meeting these requirements, the electric strain meter has been developed. It does not depend upon calibration for strain-measuring purposes, and its characteristics remain fixed. Moreover, it has a numerical "calibration" constant which for meters of the same design is practically the same.

This instrument takes advantage of the linear relationship between stress in a steel wire and its electrical resistance, and permits observations to be made of the *ratio* of two resistances which are changed in opposite directions by a given dimensional change within the structure. Within the range of the meter, the change in electrical resistance ratio is in direct numerical proportion to the change in gage length of the instrument.

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[1] Professor of Civil Engineering, Director of Engineering Materials Laboratory, Department of Civil Engineering, University of California, Berkeley, Calif.

[2] Research Engineer, Engineering Materials Laboratory, University of California, Berkeley, Calif.

The principal deformations in concrete structures are caused by variations in temperature, moisture content, and stress. The strain meter provides means for determining temperatures; consequently, deformations due to variations in temperature may be separated from those due to variations in moisture content and stress. Further, through the use of suitable controls, deformations occurring from variations in moisture content may often be separated from those due to stress. Of course, stress deformations cannot be divided into those which are purely elastic and those which involve plastic flow.

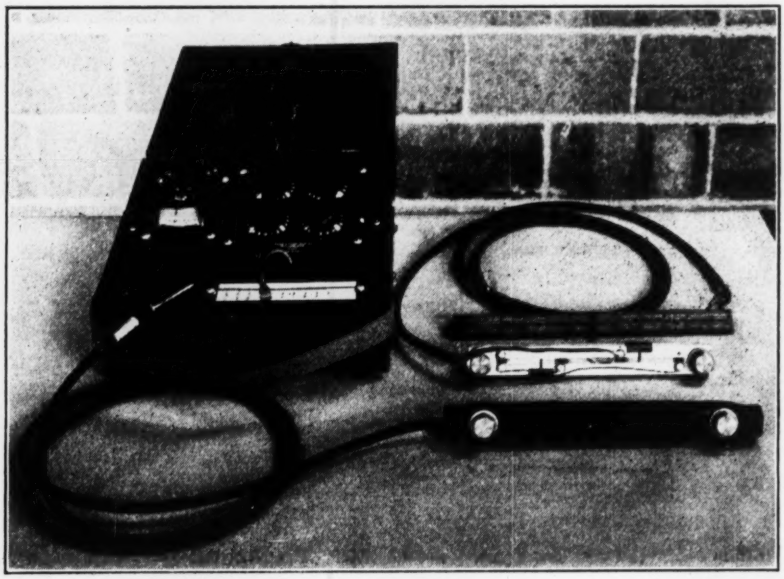

FIG. 1.—General View of Complete Apparatus, Showing Strain Meter With and Without Cover.

CONSTRUCTION

Essentially the strain meter consists of fine steel music wire, wound lengthwise in two coils on an insulating framework of porcelain. This framework, which is ordinarily of 9 to 12-in. gage length, is made up of two interlapping members, one end of each being anchored to the structure in which strain is to be measured. Changes in dimension between the gage points cause corresponding longitudinal movements between the two members of the framework, thus increasing or decreasing the tension in the coiled wires and varying their resistances. The two coils are so arranged that a movement which increases the tension in one will decrease the tension in the other. The coils are connected by lead wires to a portable testing set, forming a Wheatstone bridge circuit. Direct readings are made of the ratio of the resistances of the two coils.

Figure 1 shows a photograph of the apparatus, with a completely assembled strain meter attached to the observing instrument, and a detached strain meter without its cover in the background. Figure 2 shows the separate parts of the porcelain framework and also shows more clearly the assembly of framework and coils. On the porcelain frame pieces *AA′*, are wound wires of approximately 0.004-in. diameter, having an elastic limit in excess of 200,000 lb. per sq. in. and initially stressed to approximately 100,000 lb. per sq. in. The arrangement is such that an elongation of the instrument between gage points increases the tension in the coils *B* and *B′*, and reduces the tension in coil *C*. Coils *B* and *B′* are essentially one coil, having together the same number of turns as coil *C*. For convenience, coil *C* is called the contraction coil, and *BB′* the expansion coil. The purpose of dividing the expansion coil *BB′* is to reduce the effect of possible temperature differences along the body of the instrument. A simpler arrangement which is designed to take care of extreme temperature variations has one coil completely enclosed by the other.

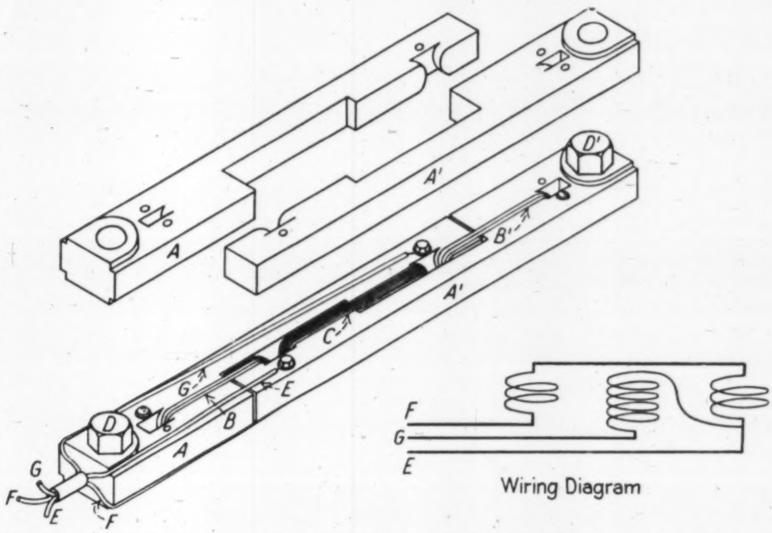

FIG. 2.—Strain Meter with Cover Removed, Showing Wiring Connections.

Initial tension is secured in the wires by connecting the central coil in place, attaching suitable weights to the free ends of each end coil, equalizing the tension in the individual strands by hand, and then clamping the wires while under tension to brass binding posts in the porcelain frame. Connections are then carefully soldered. The effects of minor stress inequalities in various turns of the coil are negligible since they do not alter the constant of proportionality between changing resistance ratios and strains. D and D' are anchor bolts which engage the concrete in which the instrument is embedded.

A three-conductor, rubber-covered cord, EFG, leads from the strain meter to a station where electrical measurements may be made conveniently. One conductor, E, is connected to a binding post in the strain meter which is common to one end of both coils. A second conductor, F, is connected to the opposite end of the expansion coil, and the third, G, to the opposite end of the contraction coil.

The framework and coils after assembly are enclosed in a protecting metal tube. A rubber cover, shown in Fig. 1, is then placed around the instrument, the interior is filled with acid-free castor oil which is non-corrosive to both rubber and steel, and the cover is then sealed. This arrangement effectively excludes air and moisture from the steel wire of the coils.

In service, the strain meter is embedded in the concrete where strain is to be measured, and the concrete is allowed to harden, thus engaging the anchor bolts but remaining practically free from frictional contact with the portion between these gage points. During this period, the halves of the framework are sometimes held in an extended position by means of small coil springs, in order that a greater range may be available for contraction measurements.

DETERMINATION OF STRAIN

For the determination of strain, the ratio of the electrical resistance of the expansion coil to that of the contraction coil is measured. This procedure has several advantages over the more obvious method of measuring absolute values of the separate resistances. When strain occurs, the resistance of one coil increases while that of the other coil decreases, affecting the ratio in *double* measure. When temperature changes occur, however, the resistances are affected in *like* measure, and the resistance ratio of the two coils remains constant. Further, the resistance ratios are not appreciably influenced by lead-wire conditions, although the individual resistances may be.

Strain cannot be determined from a single measurement, but the strain which develops over a given interval of time may be determined by comparing the resistance ratios of the two coils at the beginning and end of the period. The change in resistance ratio is simply multiplied by a constant to give "indicated" strain, the constant depending upon the design of the strain meter. The design may be made such that a change in resistance ratio of one per cent will correspond to a strain of 0.0003 in. per inch. Thus, for this specific case, it is necessary that resistance ratios be measured with a relative accuracy of not less than 0.01 per cent in order to provide a least reading corresponding to a strain of 0.000003 in. per inch.

An electrical testing set which is designed on the Wheatstone bridge principle is used to measure the resistance ratios. Since there are two nearly equal arms of the bridge in the strain meter, and also two nearly equal arms in the testing set, the problem of obtaining a relative accuracy of 0.01 per cent for the limited range required is simplified.

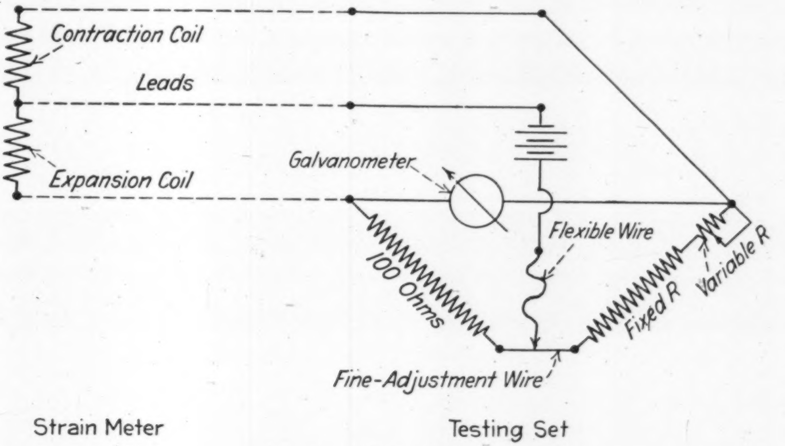

FIG. 3.—Wiring Diagram.

The complete wiring diagram is shown in Fig. 3. To take a reading, the metal tip of a flexible cord of the testing set is touched to a point on the fine-adjustment wire, and the galvanometer deflection is noted. If the galvanometer moves to the positive side of the scale, the variable resistances must be increased to bring about a balance, and *vice versa*. Coarse adjustment is made in steps through a variable resistance box; fine adjustment by touching the metal tip along various points of the fine-adjustment wire until the galvanometer deflection becomes zero. The set is graduated to indicate directly the resistance ratio of the two strain-meter coils. Having coils of nearly identical wire lengths, the resistance ratios are maintained at a value close to 1.0, varying from this value not more than 5 per cent even under maximum strain. The necessary adjustments of resistance are therefore small, and the major portion of the resistances in the testing set may be fixed, thus increasing the accuracy. Sufficient sensitivity is obtained by using a battery of 2 small dry cells having a potential of approximately 3 volts.

Although temperature changes have no direct effect upon the resistance ratios, they have an indirect effect which arises from the thermal expansion of the instrument parts. This temperature effect may be determined experimentally and a suitable correction applied, additive when temperature increases, and *vice versa*. This correction is of the order of 0.000003 in. per inch per 1° F.

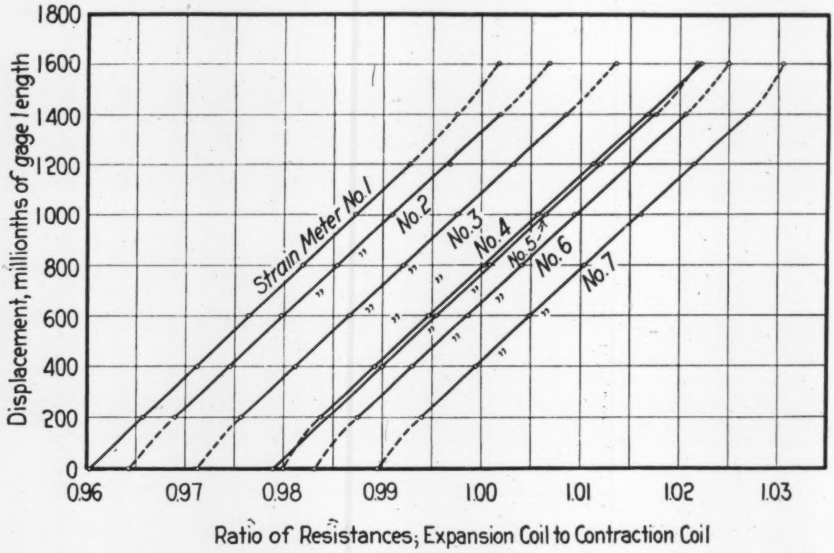

FIG. 4.—Calibration Curves for Various Strain Meters.

DETERMINATION OF TEMPERATURE

By suitable calibration before embedment, temperature readings may be made with the instrument. For this purpose, the combined resistances of the two coils are read directly by means of the portable testing set. Accuracy of the temperature readings is not materially affected by strain, since increase in resistance of one coil due to strain is offset by an equal decrease in the other.

The temperature coefficient of resistance for steel music wire wound on porcelain is approximately 0.0016 ohms per ohm per 1° F. at 70° F. Determination of temperature to an accuracy of 0.5° F. therefore requires that the sum of the coil resistances be measured to an accuracy of 0.08 per cent. Temperatures are thus obtained with sufficient precision for most purposes.

In determining strains with the instrument, it is necessary that temperatures be known in order to obtain true values of change in dimension from the indicated strains. An additional advantage of the temperature-reading feature is that changes in dimension due to temperature may be separated from the total indicated strain.

CALIBRATION STUDIES

Although calibration of individual strain meters is not necessary to determine the constant for converting resistance ratio into strain, calibration reveals the limits within which a linear relationship exists between resistance ratio and strain. The useful range as defined by these limits is restricted on the one hand by the elastic limit of the steel wire and on the other hand by the amount of initial tension. As ordinarily manufactured, the useful range of a meter having a 9-in. gage length is somewhat in excess of 0.01 in.

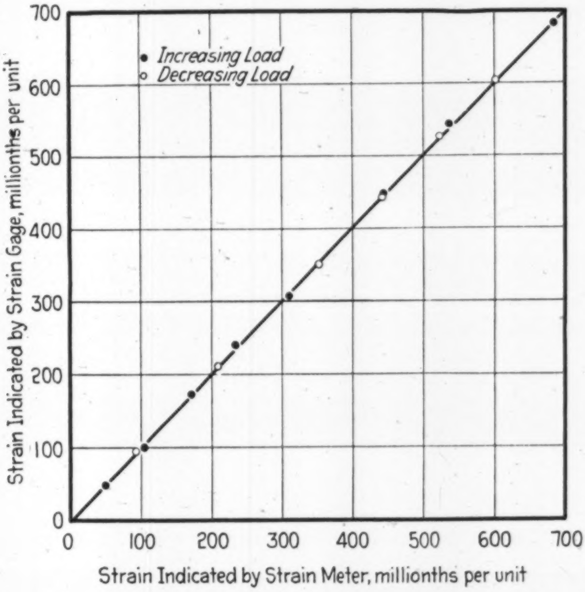

FIG. 5.—Comparison of Strains in Concrete Under Compressive Load, as Determined by Strain Meter and Strain Gage.

A similar type of strain meter has been developed to measure the relatively large movements which occur across contraction joints. These meters are necessarily of greater range, involving longer coils, and can be used satisfactorily for movements up to 0.1 in. The framework is made of steel with porcelain inserts, as lateral displacement of the joint would fracture an all-porcelain frame.

Typical calibration curves for a group of strain meters are shown in Fig. 4. The slopes of the straight portions of the curves represent the calibration constants, which are seen to be practically equal. This indicates that the same constant may be used for all instruments of similar construction. Working ranges are well defined by the straight portions of the calibration lines, which are drawn solid. It has been found after repeated trials that calibration after embedment in concrete remains the same as before.

To study the action of the strain meter under known displacements, nearly one hundred instruments have been embedded axially in concrete specimens and have been under observation for considerable periods of time under a variety of conditions. Figure 5 shows the results of a representative test made on a concrete cylinder of 6-in. diameter, loaded in compression. Strain-gage inserts were placed on three axial lines at the surface for comparative readings. The plotted points show close agreement, both under increasing and decreasing stress, with the average values obtained with a mechanical strain gage. The constant used was obtained from a calibration curve of the type shown in Fig. 4, and the results verify the accuracy of that constant. At times, slight differences in indicated strain have

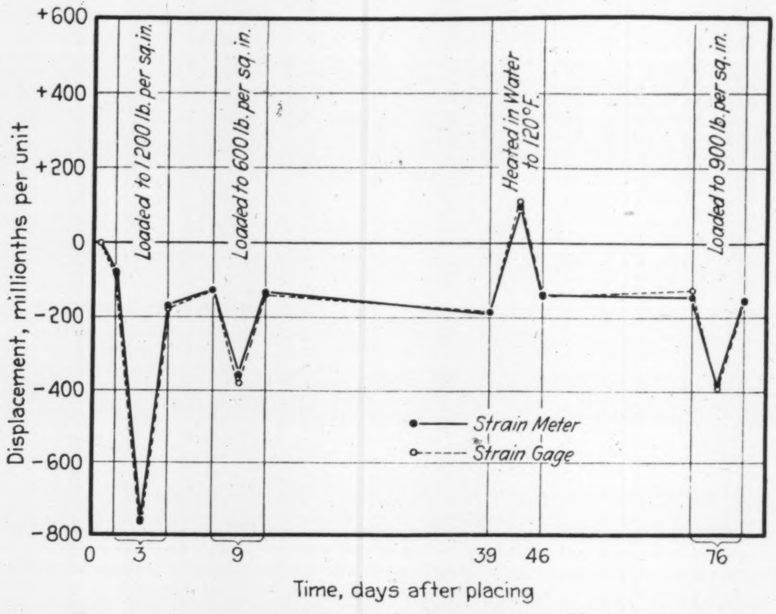

FIG. 6.—Comparison of Strains in Concrete from Various Causes, as Determined by Strain Meter and Strain Gage.

been noted between interior readings taken with an embedded strain meter and surface readings taken with a mechanical strain gage. Studies have demonstrated that these differences actually existed, due either to the non-uniform effects of temperature and moisture changes or to the non-uniform application of load.

Other tests for the purpose of verifying the results obtained with the strain meter have been made under a variety of conditions, including alternations of water soaking and drying, alternations of high and low temperatures, and alternations of load. Figure 6 shows typical results from one of these tests made over a 76-day period. Comparison is made with mechanical strain-gage measurements on a 6-in. diameter concrete specimen. The calibration constant used for the strain meter was 360 millionths for each per cent change in resistance ratio, and the indicated readings were corrected for temperature by adding 3 millionths per unit for each degree rise above 70° F. The specimen was removed from the mold at the age of one day and exposed to the laboratory air at 70° F., the strain meter registering at 3 days a shrinkage of 76 millionths per unit as compared with 82 millionths indicated by the mechanical strain gage. At 3 days a load of 1200 lb. per sq. in. was applied and released, the readings indicating a residual displacement or flow. The specimen was then left unstressed in air for 6 days, during which time a partial recovery of displacement was effected. Another load test was made at 9 days, with again a slight flow. The specimen was left unstressed in air from 9 to 39 days, when it was placed in hot water (120° F.) for 4 days, registering an expansion due to both temperature rise and moisture absorption, and a residual expansion due to the effect of moisture alone. Left unstressed for thirty days, the specimen was again subjected to a load test and the load released. During all of these treatments, the readings taken with the strain meter and strain gage were in satisfactory agreement, the meter differing from the gage by an average of less than 5 per cent. Further tests are now being carried on and will be continued for longer periods of time.

FIELD USE

A number of field installations have been made and are now under observation. The recorded measurements will enable studies to be made of the performance of the instrument under service conditions, and will make available considerable data on the strains occurring in concrete structures. About three hundred instruments have been manufactured to date, of which approximately one half have been used for development and experimental purposes, and one half in actual field service.

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